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Space Station Redesign Team Final Report to the Advisory Committee on the Redesign of the Space Station

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Space Station Redesign Team Final Report to the Advisory Committee on the Redesign of the Space Station

June 1993

NASA
National Aeronautics and
Space Administration

Washington, D.C.
20546

Reply to Attn of: VA

JUN 9 1993

The Honorable Daniel S. Goldin
Administrator
National Aeronautics and Space Administration
Washington, DC 20546

Dear Mr. Goldin:

I am pleased to formally submit the enclosed "Final Report to the Advisory Committee on the Redesign of the Space Station," in response to your request. This report is the result of contributions by a group of dedicated experts throughout NASA and from our International Partners. This report met your challenge to "significantly reduce development, operations, and utilization costs while achieving many of the goals for long duration scientific research."

Our report supports America's goal to provide future generations with a safe, affordable, and robust future in space while ensuring the greatest benefit for all people on Earth.

Sincerely,

Bryan D. O'Connor

Bryan D. O'Connor
Director, Space Station Redesign Team

Enclosure

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Introduction

In preparation for submittal of its Fiscal Year 1994 Budget, the Administration conducted an assessment of current NASA programs and projected budgets. This assessment showed that the Space Station Freedom budget would not fit within the expected NASA budget envelope given the increased emphasis placed on other agency programs, such as aeronautics and science. The President therefore directed the NASA Administrator to redesign the Space Station to be more efficient and effective, and to meet the new budget guidelines.

The NASA Administrator assembled a Space Station Redesign Team to provide several options that would significantly reduce program costs. These options should include recommendations for new streamlined management structures and acquisition strategies, as well as concepts that cut operations costs in half while still achieving the goals for long-duration scientific research. The Station Redesign Team, consisting of 45 NASA employees and 10 representatives of the International Partners established an office in Crystal City, Virginia. With the aid of five government and nongovernment consultants, and three groups of NASA engineers and scientists at Johnson Space Center, Marshall Space Flight Center and Langley Research Center, the Station Redesign Team began its redesign effort on March 10, 1993. The team is listed in Appendix A.

Goals were provided to the Station Redesign Team for a revised 10 year Space Station program, as well as specific objectives and constraints in his implementation letter of March 9, 1993 (Appendix B).

An independent senior-level panel, the Advisory Committee on the Redesign of the Space Station, was formed the first week in April to review and assess the Station Redesign Team's findings. This panel is charged with independently assessing the redesign options and proposing recommendations to improve the efficiency and effectiveness of the Space Station program.

The contributions of the International Partners in the Space Station program and the potential impact of a redesign on their ongoing efforts were recognized at the outset. A set of operating guidelines between NASA, the European Space Agency, the Canadian Space Agency and Japan's Science and Technology Agency was agreed to and signed, to ensure full participation at all levels of the redesign effort. A similar set of guidelines was signed between NASA and the Italian Space Agency.

The team conducted a significant outreach to the Space Station user community, providing briefings on the redesign process, and receiving input on science, research and technology issues and requirements.

Numerous concepts were presented to the Station Redesign Team. Input came from NASA centers, industry, the Space Station Freedom Program Office, International Partners and other interested parties. This input provided a diverse set of architectures, management and operations approaches, as well as constraints and lessons learned. The team assessed all concepts within the framework of the guidance contained in the Administrator's letter and the existing international agreements. Team members also arranged for technical briefings with a delegation from the Russian Space Program. The team soon narrowed the field to three basic design options, and focused its efforts on defining those options as thoroughly as time allowed.

The three options are Option A, Modular Buildup, Option B, Space Station Freedom Derived and Option C, a Single Launch Core Station.

This report is the result of the Station Redesign Team's activity. Its purpose is to present without bias, and in appropriate detail, the characteristics and cost of three design and management approaches for the Space Station. It was presented to the Advisory Committee on the Redesign of the Space Station on June 7, 1993, in Washington, D.C.

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Mission, Tasks and Design Guidelines

Mission

The mission of the Space Station is to provide an international Earth orbiting research facility where people live and work safely in a micro-gravity environment.

On April 30, 1993, the President's Office of Science and Technology Policy promulgated the Space Station program objectives.

Office of Science and Technology Policy Space Station Program Objectives
Create the capability to perform significant long-duration space research in materials and life sciences.
Develop the technology and engineering skills for building and operating advanced human and autonomous space systems.
Encourage international cooperation in science and technology.
Provide opportunity for new users, particularly industry users, to conduct experiments on new, commercially relevant products and processes.
Acquire new knowledge regarding the feasibility and desirability of conducting human scientific, commercial and exploration activities.

To accomplish these objectives, four basic strategies are required:

1. Build and operate a Space Station
2. Provide a platform for technology development
3. Provide an international laboratory facility
4. Integrate user outreach.

Tasks

Each of these strategies leads to specific tasks for the Space Station program. The flow of Administration objectives, implementing strategies and required tasks is shown in Figure 1. These tasks include the actual research and development disciplines to be facilitated by the Space Station. Many of these disciplines relate to basic fundamental research. A number of the tasks create the potential for near-term benefits to people on Earth. Previous research in space based laboratories has made, and will continue to make, important contributions to Earth-based technological advances and health care. In the process of exploring space, we have learned how gravity affects fundamental physical, chemical and biological processes, and in some cases, we have used space technology to fashion new products for people on Earth. Deployment and utilization of the Space Station will expand our knowledge and improve our techniques; and while it's important not to overstate the expectations, past experience shows that significant benefits may be realized by various science and engineering disciplines.

Biological And Life Sciences

The maintenance of crew health and safety requires the understanding of the mechanisms of health and disease, and leads to development of preventive methods, technologies, and treatments to maintain and restore health. The understanding of blood pressure regulation, treatments for balance disorders, and treatment of conditions responsible for muscle mass losses are specific examples of these methods and treatments.

In addition, the study of pathophysiological effects of microgravity will (1) improve the prediction of risk and prevention of kidney stone for-

OBJECTIVES	Develop the technology and engineering skills for building and operating advanced human and autonomous space systems	Acquire new knowledge regarding the feasibility and desirability of conducting human scientific, commercial and exploration activities	Create the capability to perform significant long-duration space research in materials and life sciences	Encourage international cooperation in science and technology	Provide opportunity for new users, particularly industry users, to conduct experiments on new, commercially relevant products and processes
STRATEGIES	Build and operate a Space Station Provide a platform for technical development	Provide an international laboratory facility			Integrate user outreach*
TASKS	Validate enabling technologies Gain on-orbit assembly, maintenance, operations and logistics experience Promote public awareness and scientific and engineering educational opportunities Enhance sensor technologies Verify analytical models Evolve system capabilities Create opportunties for development and test new capabilities	Improve understanding of basic fluid physics, materials and combustion processes Understand gravity mediated biological processes Support Earth observation and further characterize the environment Further characterize other environments Validate fluid physics numerical models Conduct focused biotechnology research Determine the function and structure of biological systems Determine health risk and performance for extended human spaceflight Develop countermeasures and medical capabilities		Share research benefits and cost Conduct joint research programs Achieve interoperability of systems, elements and supporting infrastructure Develop complementary systems and elements	Translate potential technologies to industry Conduct joint research programs Share research benefits and cost Sponsor dual use applied technology development Validate enabling technologies * Consistent with objectives of NASA Technical Research Initiatives/Centers for the Commercial Development of Space, etc.

Figure 1
Objectives, implementing strategies and required tasks

mation, (2) contribute to the development of noninvasive methods for detecting bone strength and mass losses, and (3) contribute to the development of exercise equipment and regimens for rehabilitation of bedridden and elderly patients.

Operations in spacecraft environments contribute to the development of portable life support systems and refined sensors. Examples are miniaturization and development of portable medical equipment, advancements in telemedicine and biotelemetry, improvements in noninvasive diagnostic imaging and monitoring of health status, development of computer-aided diagnostic systems, improved bioisolation techniques and advances in blood preservation and banking methods.

Microgravity and Commercial Research

Biotechnology

One step removed from the "whole organism approach," is the growth of three-dimensional tissues in culture where deleterious shear forces are significantly minimized. The ability to develop larger, higher-fidelity models of living tissues will improve transplant methods, cancer and antiviral therapies and drug testing. Understanding the role gravity plays at the cell level in microorganisms, plants and animals will advance our knowledge in genetic research, reproductive biology, embryonic and early development, the plasticity of the nervous system, biomineralization and the aging process. Protein crystallization in space offers the development of pharmaceuticals that use protein structural data from crystals grown in microgravity to gain a better understanding of proteins involved in disease processes, such as HIV reverse transcriptase, 2 domain CD4, human alpha-thrombin, interferon alpha-2b and others.

Fluid Physics

Fluid physics (gas and liquid) research involves behavior of fluids in both physical and biological systems where buoyancy and sedimentation effects disappear, where convective motion is minimized and where hydrostatic pressures do not influence fluid motion mechanics. Gravity is ultimately responsible for many of the aspects of fluid behavior we are accustomed to on Earth. Many of our intuitive expectations do not hold up in microgravity, however, because other forces, such as surface tension, control fluid behavior. Space offers scientists unique opportunities to explore different aspects of the physics of fluids.

The knowledge of fluid behavior gained in space is not only important to basic science, but it is also the key to new technologies. The behavior of fluids is at the heart of many phenomena in materials processing, biotechnology and combustion. Surface tension driven flows, for example, affect semiconductor crystal growth, welding and the spread of flames on liquids. Colloidal suspensions for drilling are important to the oil industry. Drop dynamics is an important aspect of chemical process technologies such as oil spill recovery, and is important in the understanding of weather phenomena. Research conducted in microgravity will increase our understanding of fluid physics and provide a foundation for predicting, controlling and improving a vast range of technological processes.

Combustion

Combustion processes play a key role in energy generation and utilization, production and control of air pollutants, transportation and propulsion, and materials processing and synthesis. Buoyancy and settling effects associated with gravitational forces preclude experiments vital to definition of combustion fundamentals on Earth. Experiments in space can add to the understanding of mechanisms involved in various types of combustion processes, leading to significant advances in combustion science. Development of a better understanding of combustion mechanisms could lead to reduced fire losses on Earth, increased efficiency of energy utilization and minimized production of pollutants and waste heat.

Materials Science

The opto-electronic and physical properties of glasses and ceramics are controlled primarily by their process-related defect structure which depends on many variables ranging from the atomic to the macroscopic. The establishment of quantitative and predictive processing and property relationships depends on knowledge of the role of transport phenomena on defect structure development. Since many of the steps involved in the synthesis and subsequent processing of these materials are accomplished in the presence of a fluid phase, gravitationally driven fluid flows can make it impossible to isolate and understand the individual elements of physics and chemistry involved. Knowledge gained in the microgravity environment may enhance ceramic chip carriers used routinely in high performance electronic devices.

Technology and Engineering Research

Research into the long-term effects of the space environment will influence the selection of materials, coatings and mechanisms for future spacecraft design. All spacecraft will become more productive and cost efficient by reducing their launch mass requirements and increasing their useful on-orbit life. Information obtained during technology and engineering research can be used to improve the characteristics of materials and coatings used on Earth-based structures and devices such as lightweight oxygen tanks, high-strength corrosion-resistant pipes, long-life self-healing paints, permanently-lubricated machinery and solar cells for power generation. The accurate knowledge and prediction capability of structural performance in microgravity can be applied to technology involving structures, structural dynamics, control structure interactions and adaptive control. New component technologies and systems, including coding, error checking and data compression methods, also can be applied commercially.

The production of more efficient space power will make the commercialization and exploration of space more cost effective and efficient. The knowledge gained from the development of closed environment life support systems has significant potential for reducing logistics for human spaceflight.

Research Requirements

The Station Redesign Team established a set of research requirements and guidelines based on a survey of recommendations and strategies developed by the science, technology and commercial communities. These included reports generated by NASA, National Research Council Advisory Committees and Space Station discipline science working groups, as well as discussions with many of the external research advisory groups. The resulting research requirements are not necessarily linked to a single facility or discipline but are intended to accommodate the needs of several research disciplines contributing to a "productive and value added science and technology." These requirements are presented in Appendix C.

Design Guidelines

Within the framework of the Space Station Program strategies, and in order to accommodate the recognized tasks of a space laboratory in low Earth-orbit, the team defined a set of top-level design guidelines. These guidelines are grouped into five sections: Administrator's guidance; science, technology and engineering research; engineering; operations; and international commitments.

Given that the objective of a Space Station is to provide a capability for people to conduct research in space, the two essential guidelines for the design must be to:

- Maintain crew safety
- Allow for maximum crew productivity.

Guided by these two overriding objectives, the Redesign Team established a set of top-level design guidelines. The source for these guidelines are:

- Existing Level I and Level II Space Station Freedom Requirements
- Coordinated user community requirements
- International Partner requirements derived from the Memoranda of Understanding
- An independent assessment of Space Station requirements conducted by a team led by Commander Jim Weatherbee (USN), Johnson Space Center.

Extensive discussions were conducted to arrive at key guidelines that should drive the option designs. Guidelines which emerged from these discussions were: simplify system interfaces, prioritize scientific tasks, reduce complex maintenance requirements and adhere to fundamental crew safety principles.

In addition to these, the independent requirements review led by Commander Weatherbee's team established a set of key philosophical design guidelines which were adopted by the Redesign Team. Those were:

- provide a means to return the crew to the ground in an emergency
- encourage the use off-the-shelf technology
- use automation, but allow for manual override by the crew where it is reasonable
- ensure the survival of the Space Station, even in the event of a severe failure such as a fire or impact from micrometeoroids or orbital debris
- accommodate a large degree of independence from the ground
- ensure that the well-being of the crew and the operability of the station does not depend on any single link with the ground
- balance the design such that no single factor or resource is notably limiting.

The full set of design guidelines can be found in Appendix C of this report.

Science, Technology, Applications and Engineering Research

Introduction

Low Earth-orbit offers a unique research environment with a near-absolute vacuum, a spectrum of radiation, temperature extremes and reduced gravitation forces. Gravity is a universal force affecting every aspect of our life, shaping all physical, chemical and biological processes. Phenomena such as sedimentation, buoyancy, fluid behavior and heat transfer and dissipation, are common to biological and nonbiological systems alike and are all influenced by gravity. The Space Station, as a permanently space-based laboratory, offers the opportunity to study fundamental processes without the masking influence of Earth's gravity.

It is well documented that the quantity and quality of data generated from orbital flight is related to the total time in orbit. This is particularly true for the biological sciences, although it is also true for some materials sciences and biotechnology. In order to fully understand the biological adaptation process, exposures exceeding 90 days are required. Research in electronic and photonic crystal growth can require up to 30 days for a single sample, while some of the most significant tissue culture research could take up to nine months.

Frequent access to the research environment allows more experiments to be performed and more data to be generated. This is critical to the advancement of individual disciplines and a requirement for commercial, government and academic programs. Without access, papers are not published, engineering designs are not verified and companies may not collect the data necessary for patent filing or technology development.

The Space Station will be an interactive laboratory in space modeled closely after those on the ground. The observations of the crew and their ability to change protocols as necessary to enhance the science is critical to the types of experiments planned for microgravity, life sciences, technology development and commercial research. A small percentage of experiments will be automated to reduce the demand on crewtime, an extremely valuable resource in space. However, in many cases experiments either cannot be automated, or the cost to automate them is prohibitive. The crew is expected to be the researchers, as well as the subjects, for many of the life science experiments that will investigate how human physiology is affected by microgravity. These experiments will provide information that relates to the physiology of humans on Earth, as well as provide the basic data required to enable humans to live and work productively in space for extended periods of time.

The NASA engineering research and technology program in space has been recognized by advisory bodies, including the National Research Council, as an important contribution to United States competitiveness. NASA was tasked to define and develop experiments to support the engineering technology needs of "industry, other government agencies and universities, as well as its own laboratories for all in-space engineering." It is an integral part of NASA's mission to use the Space Station as an engineering laboratory and technology testbed to enhance our ability to validate high-leverage technologies that can reduce the cost of future space systems. These technologies, in turn, will enable research thrusts that will challenge or validate current theories, identify or describe new physical phenomena, and foster acquisition of new knowledge from unexpected discoveries which is perhaps the most exciting product of space research.

Scientific discovery can lead directly to new applications. For example, some protein crystal and electronic materials research in space explores the physics and chemistry of processes involved in the production of pharmaceutical and electronic components, respectively. Other protein crystal growth studies add substantially to our fundamental scientific knowledge, but may not necessarily have obvious practical applications. Similarly, electronic and photonic materials research focuses both on the basic principles of crystallization transport kinetics and on production technologies of interest to United States industry. The existing synergism and interdependency between scientific and technical research objectives is the guiding principle for the development of requirements for all space-based laboratories and implementation of scientific priorities.

The Space Station is a logical extension of the ongoing United States and international space programs in biological and microgravity sciences, technology and engineering research and applications. It creates opportunities for private sector investment, international cooperation and education.

Important determinants of Space Station productivity are the quality and quantity of such resources as: crew time, volume, power, levels of microgravity and available research instruments at any given time. In providing any new capability, careful consideration should be given to adequately match research discipline needs with the appropriate platform. The Space Station should be considered within the context of an integrated orbital research program that maximizes the effective use of available opportunities. The Space Station program complements existing ground-based university-government-industry laboratories, drop towers, sounding rockets, aircraft, freeflyers, Space Shuttle, Spacelab and Spacehab missions and Mir.

While NASA has developed and implemented strategies and outreach programs for involving universities and the private sector in the space program, it must continue to demonstrate that such strategies are effective and in the interest of the scientific and private entities. Some commercial organizations are convinced that space holds promise for enhancing their product, process or service in such a way that it may give them a competitive edge. In the future, the identification of technology needs, the development of research strategies to provide solutions to those needs, and the transfer of that knowledge to the appropriate user, should be an integral element of the orbital research program.

The orbital research program is also an essential ingredient contributing to the knowledge required for the maintenance of crew health in space missions over extended periods of time, and the testing of medical and life support systems in preparation for exploration-class missions. Assurance of the health, safety and productivity of humans in space is one of the primary roles of biomedical and biological research. Health risk assessment and management is a critical deliverable of this program. The information used from the risk categorization and estimation will help to determine the actions required to reduce or eliminate a particular risk. These health risk areas focus on the impact to the individual, but in most cases, inflight manifestations of the risk could dramatically alter the outcome of a mission. Although it will not be possible to entirely eliminate all risk to the crew, United States and Russian space flight experience indicates that a better understanding of the risks is necessary in order to develop appropriate procedures for mission success.

Experience has shown that advances in space technology provide the tools needed for space science, and in turn, scientific research leads to the development of new technology. The knowledge that flows from scientific research and technology development in space benefits people on Earth by speeding progress in fields such as medicine and advanced materials, by enriching science and education at all levels, and by enabling the development and transfer of new technologies. This knowledge also plays a critical role in enabling future exploration missions.

The following research, technology development and associated commercial and engineering areas were considered for each Space Station design:

- Technology and engineering research such as design, deployment, construction and operation of large structures and research on various materials and processes in space, to include space qualification of systems, subsystems, electronics and materials which might be used in new spacecraft.
- Microgravity sciences and applications to include biotechnology, fluid physics, combustion and material sciences.
- Biological and life sciences encompassing gravitational biology, human biology, environmental health, radiobiology, regenerative life support systems, human factors and exobiology.
- Space and Earth sciences such as astrophysics, space physics and atmospheric sciences.

The following sections describe the minimum science and technology discipline requirements, the traffic model process used to populate the options and the evaluation process used to assess the redesign options. Not included in the evaluation of research capabilities of the various options are the development of life support and medical care capabilities. These are incorporated as subsystems in each option and budgeted by the option.

Process and Methodology

The science, technology, applications and engineering research redesign team was tasked with evaluating each of the three Space Station options for its research capability, and developing a research program strategy constrained by $1.5 billion over a five year period (1994 to 1998). This funding includes research facilities being developed for the Space Station and flight opportunities that are planned by the NASA research organizations beyond the 1995 budgetary horizon. This includes a number of Spacelab modules (e.g., Microgravity Sciences Lab; and Space and Life Sciences Neurolab), pallet flights and cooperative research on the Russian Mir.

Assessing the Needs of the Research Community

For this redesign activity, the following process and methodology was used to assess and verify the needs of the research community as they relate to the microgravity and engineering research disciplines:

- Surveyed and reviewed recommendations and strategies developed by the science, technology and commercial communities (e.g., reports generated by NASA, National Research Council advisory committees and Space Station discipline science working groups);
- Reviewed the Space Station Freedom research requirements data base;
- Updated the science, technology and commercial requirements in light of recent ground and flight investigation results;
- Discussed research requirements with the International Partners;
- Discussed research requirements and related strategies with NASA advisory groups and selected representatives from industry and academia as shown in Table 1;
- Reviewed and validated the Space Station research facility data base as shown in Table 2;
- Adopted a "strategy to task" approach to define research requirements to apply to the redesigned Space Station options.

Table 1
NASA Space Station advisory groups

Aeronautics and Space Engineering Board Committee on Space Station
Aerospace Medicine Advisory Committee
Centers for the Commercial Development of Space (4)
National Research Council - Space Studies Board
Space Science and Applications Advisory Committee
Space Station Advisory Committee
Space Station Science and Applications Advisory Subcommittee
Space Systems and Technology Advisory Committee
Task Group on Utilization and Operations, Space Station Advisory Committee

Table 2
Space Station research disciplines and experimental facilities

Program	Facility or Device	Research Discipline(s)	Volume or Rack #	Nominal Power (kW)
NASA Microgravity and Life Sciences Research	Biotechnology Facility (BTF)	Biological Tissue Cultures Protein Crystal Growth	1	2.5
	Space Station Furnace Facility (SSFF)	Materials Sciences Electronic Photonic Metals/Alloys Glasses Ceramics	3	5.3
	Fluid Physics Dynamics Facility (FPDF)	Colloids and Electrohydrodynamics Critical Point Phenomena Interface Dynamics Multiphase Flow and Heat Transfer Surface Tension Coalescence Convective-Diffusive Transport Processes	3 (Common Core Rack shared with MCF)	2.5
	Modular Combustion Facility (MCF)	Combustion	(Common Core Rack shared with FPDF)	2.5
	Middeck Class Payloads (MDC) which include Space Acceleration Measurement System (SAMS)	Multidiscipline	1.0	2.5
	Microgravity Science Glovebox (MSG)*	Multidiscipline	1	1.8
	Gravitational Biology Facility (GBF)	Plant Biology Developmental Biology Cell Biology Neurobiology Gravity Sensing Structural Biosystems	2	2.0
	Human Research Facility (HRF)	Space Physiology Cardiopulmonary Musculoskeletal Neuroscience Regulatory Physiology Environmental Health Operational Medicine Radiation Biology Human Factors, Behavior and Performance	4	3.08
	Habitat Holding System (HHS)	Gravitational Biology Developmental Biology Cell Biology Plant Biology Radiation Biology Closed Loop Life Support Systems Research Environmental Health	1	1.82
	Life Sciences Glovebox System		1	1.83

* Not funded by Microgravity Science and Applications Division

Table 2
Space Station research disciplines and experimental facilities (cont'd)

Program	Facility or Device	Research Discipline(s)	Volume or Rack #	Nominal Power (kW)
NASA Microgravity & Life Sciences Research (cont'd)	2.5 m Centrifuge Facility (CF)	Gravitational Biology Plant Biology Developmental Biology Cell Biology Neurobiology Gravity Sensing Structural Biosystems Radiation Biology Environmental Health	5.6 m^3	2.65
	Controlled Ecological Life Support Systems (CELSS) Test Facility (CTF)	CLLSS Research Gravitational Biology Plant Biology	2	3.0
	Gas Grain Simulation Facility (GGSF)	Exobiology	1	1.0
	Human Health Maintenance Facility (HHMF)	Operational Medicine Human Biology and Physiology Radiation Biology Environmental Health	2	2.4
Office of Advanced Concepts and Technology	Commercial Microgravity Robotic Facility (CMRF)	Robotics	1	3.0
	Robotic Service Vehicle for the Wake Shield Facility (RSV)	Robotics	2.5 m^3	0.5
	Space Environment Monitor System (SEMS)	Environmental Effects	0.25 m^3	0.03
	Long Duration Space Experiments (LDSE)	Environmental Effects	0.75 m^3	0.82
	Spacecraft Materials and Coatings Facility (SMC Fac)	Environmental Effects	8 m^3	TBD
	Spacecraft Materials and Coatings (Internal) (SMC Exp [Int])	Environmental Effects	0.1	0.05
	Spacecraft Materials and Coatings (External) (SMC Exp [Ext])	Environmental Effects	0.33 m^3	0.46
	Hydrogen Maser Clock (HMC)	Environmental Effects	0.16 m^3	0.34
	Optical Properties Monitor (OPM)	Environmental Effects	0.24 m^3	0.25
Engineering Research	Polymer Matrix Composites (PMC)	Environmental Effects	0.9 m^3	0
	Modal Identification Experiment (MIE)	Structures	N/A	0.35
	Flight Dynamics Identification (Internal)	Structures	0.8	0
	Flight Dynamics Identification (External)	Structures	18 m^3	0.7
	Large Deployable Reflector Structural Experiment (Internal) (LDR)	Structures	1	0.2
	Large Deployable Reflector Structural Experiment (External) (LDR)	Structures	250 m^3	0
	Strain and Acoustic Sensors (External) (SAS)	Structures	0.027 m^3	0.3
	Strain and Acoustic Sensors (Internal) (SAS)	Structures	0.1	0.3
	Thermal Interface Technology	Structures	0.85 m^3	2.5
	Foam Structure	Structures	3 - 12 m^3	1.0

Table 2
Space Station Research disciplines and experimental facilities (cont'd)

Program	Facility or Device	Research Discipline(s)	Volume or Rack #	Nominal Power (kW)
Office of Advanced Concepts and Technology (cont'd)	Information Science Experiment System (ISES)	Information Systems	0.2	0.05
	Transient Upset Phenomena (TUP)	Information Systems	0.2	0.25
	Microelectronics Data	Information Systems	N/A	0.25
	Advanced Sensor Development/ Manned Observation Techniques (ASD/MOT)	Communications and Information Systems	1	0.5
	Pointable Interactive Monitoring System (PIMS)	Remote Sensing	0.5 m^3	0.0375
Engineering Research	Electric Propulsion Orbital Platform (EPOP)	Propulsion	2 m^3	2
	Cryotank Servicing Equipment	Fluid Management	N/A	1
	Regenerative Life Support Processes (RLS)	Human Support	1	3
	In Situ Trace Contaminants (ISTC)	Human Support	0.2	0.06
	Acoustic Control Technology (ACT)	Human Support	0.2	0.1
	Microbiological Monitor	Human Support	0.5	0.5
	Pressurized Small and Rapid Response (PSARR)	Multidiscipline	0.1	0.12
	Attached Small and Rapid Response (ASARR)	Multidiscipline	N/A	1
Commercial Biotechnology and Materials Research	Generic Bioprocessing Rack (GBR)	Cell Biotechnology	0.5	0.1
	Module for Integrated Cell Research in Orbit (MICRO)	Cell Biotechnology	0.5	0.05
	Physiological Testing and Biomodule	Cell Biotechnology	0.06	0.01
	Materials Dispersion and Cell Bioprocessing Applications Project (MD/CBAP)	Cell Biotechnology	1	0.1
	Telemicrosopy	Cell Biotechnology	0.15	0
	Test Module for Plants and Organics (TeMPO)	Plant Biotechnology	0.5	0.1
	Bioregenerative Water System (BWS)	Plant Biotechnology	1	1
	Protein Crystal Growth-1 (PCG-1)	Macromolecular Crystal Growth	1	0.6
	Protein Crystal Growth-2 (PCG-2)	Macromolecular Crystal Growth	1	0.6
	Organic Separation by Phase Partitioning (ORSEP)	Separation and Purification	0.07	0.18
	Commercial Electrophoresis Program (USCEPS)	Separation and Purification	1	0.5
	Physiological Systems Experiment (PSE)	Physiological Testing	0.18	0.1
	Biomedical Isomorphisms Test Equipment (BITE)	Physiological Testing	0.5	0.23
	Battelle Commercial Mixed Oxides Program (CMOX)	Zeolites and Catalysts	1	0.71
	Battelle Zeolite Crystal Growth-1 (BZCG-1)	Zeolites and Catalysts	1	0.3
	Battelle Zeolite Crystal Growth-2 (BZCG-2)	Zeolites and Catalysts	1	0.3
	Vapor Transport Facility (VTF)	Electronic and Photonic Materials	1	1.0
	Commercial Float Zone (CFZ)	Electronic and Photonic Materials	1	2.5

Table 2
Space Station research disciplines and experimental facilities (cont'd)

Program	Facility or Device	Research Discipline(s)	Volume or Rack #	Nominal Power (kW)
Commercial Biotechnology and Materials Research (cont'd)	Commercial Crystal Growth from Solutions (CCGS)	Electronic and Photonic Materials	0.5	1.0
	Commercial Crystal Growth Furnace (CCGF)	Electronic and Photonic Materials	0.2	0.1
	Sintered and Alloyed Materials (SAAM)	Metals and Alloys	1	0.5
	Liquid Stream Technology (LST)	Operations	N/A	1.0
	Risk-Based Fire Safety (RBFS)	Operations	0.3	0.25
	Proton Exchange Membrane Fuel Cell (PEMCELL)	Space Power	0.3	1.5
Space Science	Stratospheric Aerosol and Gas Experiment (SAGE III)	Earth Atmospheric Sciences	0.1 m^3	0.015

Identification and Development of Research Requirements

A set of minimum "core" user requirements was evolved and presented to the International Partners and the various representatives of the user disciplines and the advisory groups. The resulting minimum research requirements generally reflect existing strategies for Space Station utilization; they are not necessarily linked to a single facility or discipline but are intended to accommodate the needs of several research disciplines contributing to productive and value added science and technology. Most of these requirements reflect current Space Station Freedom requirements. Some reflect a compromise in total capability (e.g., volume and external attach points), and others reflect research community requirements that are not yet incorporated into the Space Station Freedom program, but are either deemed critical to capability or were funded separately through other programs. These requirements are summarized in Table 3, and are listed in Appendix C under Design Guidelines.

Research Priorities

A research prioritization strategy was constructed based on the development and buildup of each option and incremental availability of resources. Selection of disciplines was also influenced to some degree by the interdependency and potential synergism of science objectives.

Microgravity Sciences
- Biotechnology
- Fluid Physics
- Materials Science
- Combustion

Technology and Engineering Research
- Modal Identification
- Exposed Facilities (Materials and Coatings)
- Robotic Servicing
- Electric Propulsion
- Foam Structures
- Strain and Acoustic Sensors
- Thermal Interface Technology
- Flight Dynamics Identification
- Pointable Interactive Monitoring System

Biological and Life Sciences
- Gravitational Biology
- Human Biology
- Radiation Biology
- Human Factors/Behavior/Performance
- Controlled Ecological Life Support
- Exobiology

Space Sciences
- Atmospheric Sensing

Commercial Research
- Biotechnology
- Materials Science

Table 3
Space Station orbital research guidelines

Research and Capability Requirements	*Crew Size and Duration:*	• Provide the minimum science and engineering research requirement of two payload dedicated crew for 90 day increments beginning at Human Tended Capability. ●
	Power:	• Provide average 30 kW power for users when the International Partners are accommodated. ● • Provide minimum 12 kW continuous power to an individual payload located in the minimum acceleration area (0.707 x 10^{-6} g for 0.01 Hz to 0.10 Hz). ● • The external attach points should be provided with not less than 3 kW. ● • Have 28v DC and 120v AC available to payloads (local conversion is acceptable). ❑
	Volume:	• Have no less than 35 cubic meters available to all users when the International Partners are accommodated. Thirteen cubic meters for payloads at human tended capability (assume International Standard Payload Rack). —
	Atmosphere:	• Provide normoxic conditions, 21 percent oxygen, maximum 0.3 percent carbon dioxide. (The requirement may be implemented at the rack level.) ●
	Microgravity Environment:	• Comply with the Space Station Freedom 1992 PDRD requirement for acceleration levels vs. frequency and associated constraints. ● • Have an acceleration mapping system consistent with current Space Station Freedom baseline. ● • Have a vibroacoustic control plan which can be verified through a combination of ground modeling and testing and on-orbit verification. ●
Communications and Data		• Provide compressed video downlink. ✚ • Provide a total downlink capability of not less than 50 Mbps (both tended and untended). ● • Provide uplink video channel. ✚ • Provide total uplink of: not less than 72 kbps, Spacelab equivalent for stored program commands and transfer to Dedicated Experiment Processors, available in both untended and tended operations. ● • Video interface and switching with not less than four payload video cassette recorders. ❑ • Provide a data outage recorder with enough capability to capture downlink data with Loss of Signal to the users not less than Spacelab. ●
External Research Provisions		• Not less than four external attach points (including the International Partner's locations). — • Locate external attached points in order of following priority: Nadir (e.g., sensor development), ram/wake/port/starboard (e.g., engineering materials exposure), zenith (e.g., celestial viewing), active cooling *desirable* — • 10 Mbps downlink capability. ● • Uplink command capability. ●
Research Resources		• Nitrogen purge supply for furnaces, combustion facilities, etc. ● • Potable research water. ● • Nonhazardous experiment gas venting. ● • Optical viewing window. ✚ • Provide payload access to both air and water cooling. ●
Operations and Logistics		• Provide capability to change-out payloads during the lifetime of the station. ● • Provide user access to the Space Station for samples, equipment, etc., with late access for launch at the launch site and early access at the landing site. ● • Provide users with logistical resupply of samples, equipment, etc., in pressurized, powered modules, insuring that animals, refrigerated samples, etc., are returned to researchers in a reasonable time. ◆ • Provide human physiological baseline data collection capability (current Shuttle/Spacelab capability is acceptable) at the landing site. ● • Include distributed science operations centers that will use commercial and NASA institutional audio, video and data communications systems. ◆ • Accommodate the United States position: *Integrated* United States payload training should be consolidated at a single location. ◆

● Equal to Space Station Freedom capabilities
— Less than Space Station Freedom capabilities
◆ Unresolved in current Space Station Freedom program
❑ Originally budgeted by users, now in common "budget box"
✚ Prior user requirement not met by Space Station Freedom but "added"

An integrated prioritization between the disciplines was completed during the course of developing "traffic models" for each redesign Space Station option, but the rationale for that prioritization was a function of several parameters: (1) existing agreements between the discipline organizations that relate access to percentage of volume available (used for existing Space Station Freedom "payload traffic models:" e.g., approximately 40 percent for engineering research and technology, 30 percent for microgravity sciences, and 30 percent for biological sciences), (2) the capabilities of the Space Station design and other orbital platforms to accommodate the research discipline, and (3) availability of funds for science and technology research.

The capabilities of each option were matched against the individual discipline research goals, both in the 1994 to 1998 time frame, and within the lifetime of the Space Station: 2000 to 2010. The process of identifying the order in which research facilities populated the various Space Station design options as a function of time required a prioritization within and among disciplines and resulted in option based "traffic models." The development of these traffic models also required an assessment of the interdependency of research objectives, the use of shared facilities and logistics support. If deficiencies in research capability were identified, then additional flight opportunities were planned within the context of a comprehensive Orbital Research Program using a variety of platforms (e.g., Spacelab, Mir, Spacehab, Space Shuttle middeck, freeflyers).

The traffic models were guided by several assumptions and constraints: (1) no more than eight Space Shuttle flights per year, (2) maximum Space Shuttle on-orbit flight duration of 20 days until 2000, then increase to 30 days, (3) utilization flights generally separate from logistics and resupply flights, (4) for Human Tended Capability options, three visiting flights per year with one or two Spacelab flights added, as required and (5) the development of research priorities given constrained resources.

Although these integrated traffic models also contain use of Spacelab and other platform flights for the period up to 2001, the most rigorous evaluation was directed to Space Station utilization. Specific discussions related to the research budget numbers and spread are not included here but may be found in the Costing Section. An example traffic model is shown in Tables 4 and 5 for Option B at Permanent Human Capability. It includes both internal and attached payloads.

Table 4
Space Station attached payload traffic model for Option B through Permanent Human Presence

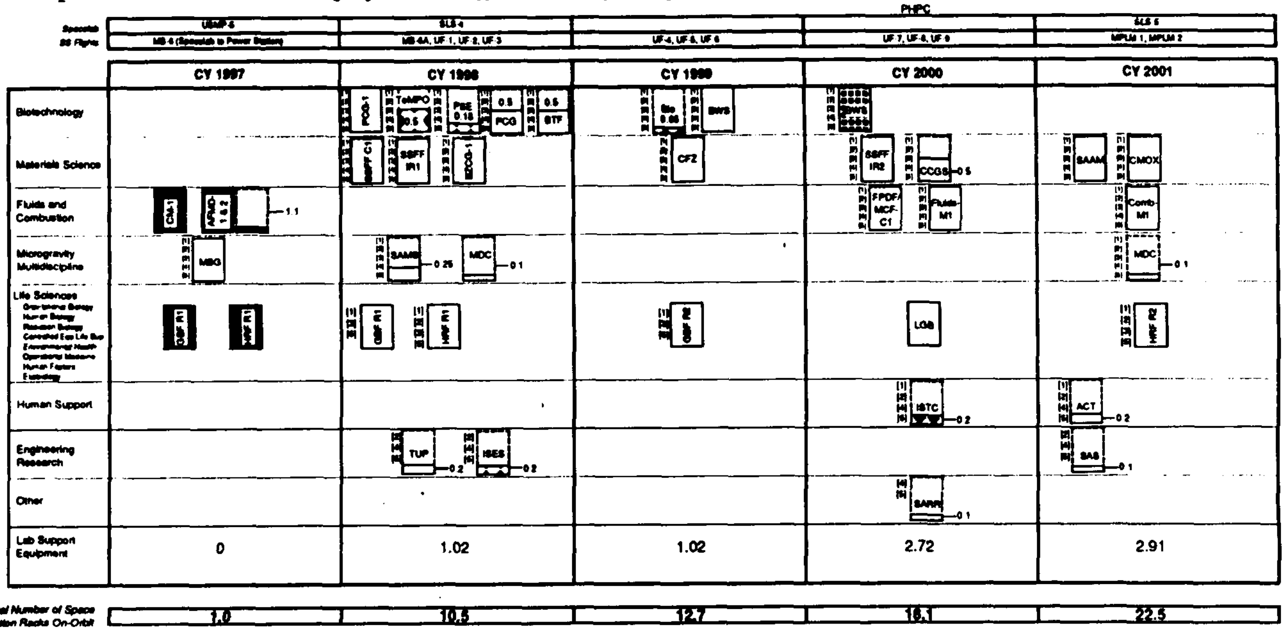
	CY 1997	CY 1998	CY 1999	CY 2000	CY 2001
Structures	[2] [4] [5] Modal Identification Experiment (Launched w/FEL in 1996)				Strain and Acoustic Sensors †
Environmental Effects		[1 - 5] Spacecraft Materials and Coating Facility Hydrogen Maser Clock* Optical Properties Monitor*	Long Duration Space Exposure* Space Environment Monitoring System*	Attached Small and Rapid Response*	Polymer Matrix Composites* Microelectronics Data*
Space Science			SAGE III		
Other					[4] [5] Pointable Interactive Monitoring System EPOP

*These payloads are part of the Spacecraft Materials and Coatings Facility.
†These payloads are part of the Modal Identification Experiment.

Space Station Program Objectives

[1] Create the capability to perform significant long-duration space research in materials and life sciences
[2] Develop technology and engineering skills necessary to build and operate advanced human and autonomous space systems
[3] Encourage international cooperation in science and technology
[4] Provide opportunity for new users, particularly industry users, to conduct experiments on new, commercially relevant products and processes
[5] Acquire new knowledge regarding the feasibility and desirability of conducting human scientific, commercial and exploration activities

Table 5
Space Station attached payload traffic model for Option B through Permanent Human Presence



NOTE: Chart does not reflect hardware on dedicated SLS and MSL Spacelab flights.

NOTE: Centrifuge launched in CY 2004

Space Station Program Objectives

[1] Create the capability to perform significant long-duration space research in materials and life sciences

[2] Develop technology and engineering skills necessary to build and operate advanced human and autonomous space systems

[3] Encourage international cooperation in science and technology

[4] Provide opportunity for new users, particularly industry users, to conduct experiments on new, commercially relevant products and processes

[5] Acquire new knowledge regarding the feasibility and desirability of conducting human scientific, commercial and exploration activities

Space Station Rack
Spacelab Rack
Returned Rack
Space Station Racks returning in same year

TOTAL FOR CURRENT YEAR =
(Rounded to the Nearest Tenth)
Previous Year Total
+ Changes in LSE
+ Current Year Racks
- Current Year Returned Racks
- Previous Year Racks Returned in Same Year

Functional Evaluations

The functional evaluations for each option depend upon both discrete research criteria for individual disciplines (e.g., microgravity and carbon dioxide levels) and the total capability for the laboratory with respect to resources including power, volume and crew time. Prior to the station redesign effort, the research community had identified the Space Station payload and experiment facilities (Table 2). These facilities and their requirements (e.g., power, volume, run time, annual run frequency, microgravity requirements and logistical supply) were matched against the Space Station Freedom capabilities. For example, one of these facilities, the Space Station furnace facility, is shown in Figure 2. The facilities were assumed to run with 50 percent power duty cycle (only 50 percent powered at any one time). A collective utilization plan developed by a representative users group prioritized the order in which facilities would be integrated into the Space Station and operated. In most cases, given the Space Station power and volume, the limiting variables for these experiment "traffic models" were crew time and logistical resupply. The science, technology, applications and engineering research group verified the Table 2 data base, and it is against this collective research population that the options are measured.

Research requirements become discriminators for what research can be conducted on a given platform, for example:

Research requirements:

Measurable microgravity levels
Carbon dioxide concentrations
Orbital research duration
Availability of crewmembers
Methods to capture data (e.g., video, downlink and storage)
Stable pointing for externally attached payloads
Experiment resources for facilities (e.g., power and venting)
Well trained crewmembers.

Other parameters measure the capability and "potential" productivity, for example:

Capability and productivity measures:

Total crew research hours per year

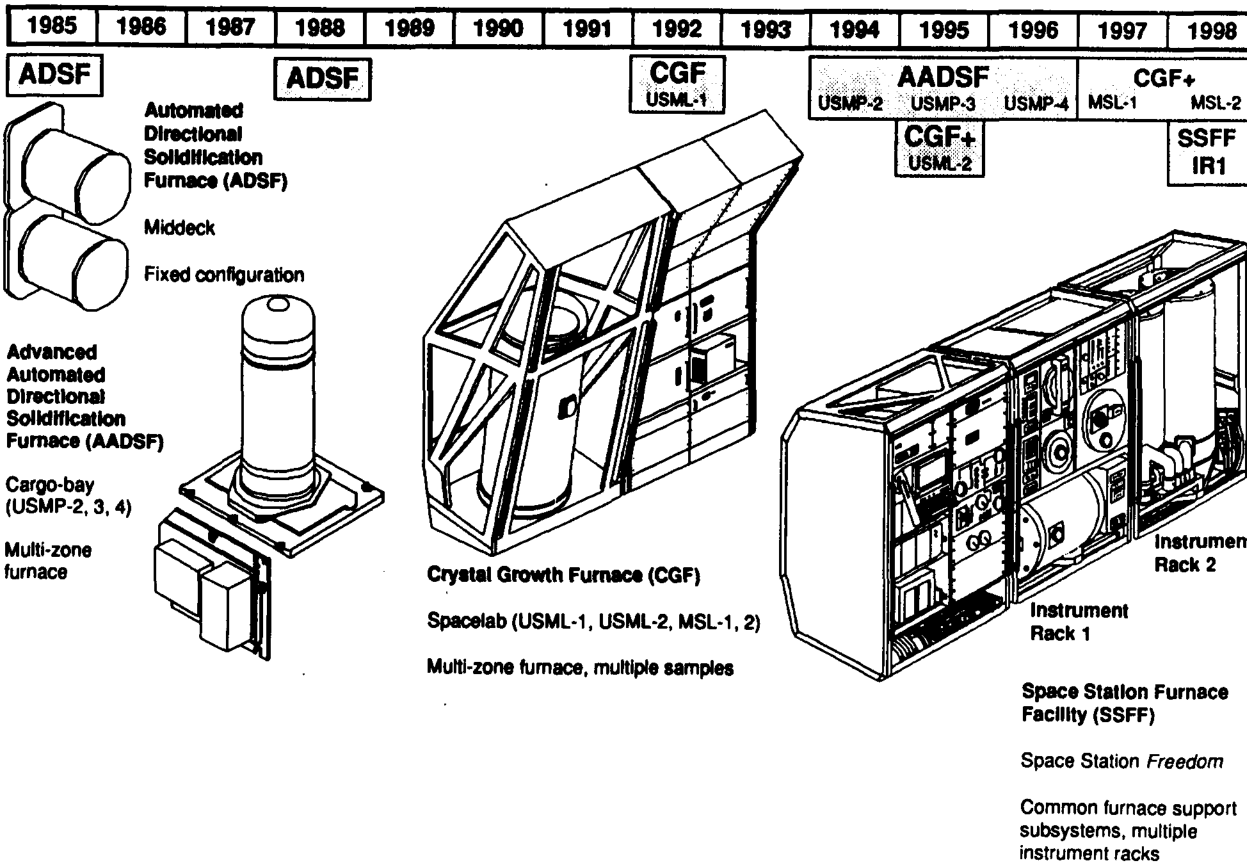


Figure 2
Solidification research program evolution

Total number of users
Total power
Total volume per time user racks are active
Total data generation and storage capability
Logistical flexibility and frequency (late and early access for powered perishable payloads and resupply; use of the rack).

Results of the functional evaluations are in the Option Assessment and Evaluation section of this report. A more detailed evaluation is shown in Appendix F.

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Common Option Considerations

Design Process

Three Space Station redesign option families were chosen for further definition based on Space Station Redesign guidelines, cost constraints, basic spacecraft design considerations, and heritage from hardware under development or in existence. A Station Redesign Team member was named to lead each option activity. Design Support Teams were established at three NASA centers to perform the detailed engineering for the options. No individual center possessed the expertise needed in all areas, therefore, each team had members from each of the following NASA centers: Johnson Space Center, Marshall Space Flight Center, Langley Research Center, Kennedy Space Center and Lewis Research Center. The three options are: A–Modular Buildup, B–Space Station Freedom Derived and C–Single Launch Core Station.

The teams were required to define all aspects of a Space Station program including detailed technical designs, operations, test and verification, logistics, ground processing and management structures. The specific products from the overall design effort for each of the options are the detailed design concept reports and backup data books, top level guidelines, option specific guidelines and unresolved issues. In addition, the program costs for each option were developed and are included in the cost section of this report.

Design Constraints

A number of requirements and guidelines were identified to be common design constraints for all options. These constraints are listed in Table 6.

Budget constraints have a significant impact on the design of all the options. To save cost, design support teams were encouraged to find design innovations, reduce requirements, substitute off-the-shelf subsystems and equipment for high cost hardware, improve efficiency of existing designs, eliminate unnecessary functions, accept a higher degree of risk or reduce user resources. At the same time, they were asked to make maximum use of existing Space Station Freedom subsystems and equipment where it made sense to do so considering the advanced state of design of much of the subsystems and equipment.

The micrometeoroid and orbital debris model, radiation, and solar flux models used in the redesign effort were adopted from those used for the Space Station Freedom program and Space Shuttle program. These were adjusted for the particular launch azimuth assumed.

All three options were evaluated at the 28.8 degree orbit inclination as well as at 51.6 degrees. Although the higher inclination results in less performance from the Space Shuttle by 12,800 pounds, it provides capabilities that do not exist at the lower inclination. In the following sections of the report, each design option is described at 28.8 degrees with the implications of flying to 51.6 degrees also addressed.

Added Capability at 51.6 Degrees
Dual Access (to reduce long term technical risk) • Resupply by Russian launch vehicles or Ariane • Human Soyuz launched from Russia, docked at station for use as assured crew return • Backup human launch capability during periods when shuttle is not available
Increased Coverage for Earth Observations
Increased Power Profile

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Table 6
Design constraints

Design Constraints	
Budget:	Reduce development costs Operation costs cut in half
Schedule:	Initial on-orbit research capability—1997 Complete development—1998
Science Guidelines:	30 kW to users after International Partners are present Microgravity environment Data requirements Volume Atmosphere quality
Reduced Technical Risk:	Minimum extravehicular activity Minimum assembly flights
Orbital Inclination:	Lift capability and debris environment
Accommodation of International Partner Commitments:	Interfaces Power and other resource requirements
Safety Requirements:	Assured crew return Fire detection and suppression Micrometeoroid and orbital debris protection
Shuttle Constraints:	Launch mass and payload bay dimensions, where appropriate

Inherited Issues

The Station Redesign Team inherited unresolved technical issues and design problems from the Space Station Freedom program. Some of the technical issues are:

- International Partner control masses are not baselined in Space Station Freedom requirements. Both the Japanese Experiment Module and the Columbus Attached Pressurized Module are currently baselined to fly on the Space Shuttle with advanced solid rocket motor and are too heavy without it. The current Japanese and European module masses require the availability of the advanced solid rocket motor at this point in the development program. However, the advanced solid rocket motor program schedule has been slipped so that the motors are not available to meet international launch date needs. If, in addition, the international modules must be launched to a 51.6 degree inclination, the new lightweight aluminum lithium external tank upgrade, as well as the advanced solid rocket motor, are required for Space Shuttle delivery of the modules. An alternate approach, such as delivery to a lower altitude, delivery by an expendable launch vehicle, redesign of the modules or schedule slip will have to be studied and baselined.
- The United States Space Station Freedom module design does not meet the program micrometeoroid and orbital debris requirement because the environment has changed since the design was frozen. A final risk trade to address this issue has not yet been completed.
- Maintenance during assembly of Space Station Freedom falls behind, creating a maintenance backlog of failed equipment. This backlog is due to lack of sufficient extravehicular activity hours available on Space Shuttle flights after the assembly tasks are completed.

- Space Station Freedom hardware development schedules are described as 'just-in-time to meet launch dates.' Schedules are further complicated by the overlap in qualification and verification testing schedules with the schedules for the production of flight hardware. These schedule issues result in significant schedule and cost risk.
- Funding for flight hardware spares and ground support equipment for the program has been deferred due to Congressional budget reductions, leading to an inability to obtain spares on an efficient production schedule for availability need dates.
- The data management system is a highly complex system which has a high development cost for hardware and software, as well as for test and verification. This system also has high mass and power requirements. Because of the planned high degree of automation for Space Station Freedom, the data management system is designed to be a very pervasive system which manages operations, and controls and monitors all station hardware and systems. This makes it difficult to upgrade or switch to other system designs to achieve greater efficiency and reduce integration complexity.
- The assured crew return vehicle is not funded.
- Several Space Station Freedom system designs, which were used in redesign team options, have cost overruns and development schedule problems.
- Structural load issues exist during docking when using the Russian docking mechanism (Space Shuttle and Space Station interface issue).
- Unresolved issues exist in agreements with International Partners, such as the number of simulation trainers to be provided to training facilities, personnel to be provided to support real time operations, and a cost policy for Space Shuttle transportation.
- Space Shuttle orbiter reaction control system plume impingement effects on the solar arrays need further analysis and may require modification to the orbiter thrusters.

Systems Design

The systems design and interface complexity are powerful factors in hardware and program integration costs. Complexity, technical issues and significant conservatism exist with current Space Station Freedom systems designs. The design support teams were encouraged to simplify existing designs or find more efficient solutions to provide the required system functions. However, it is important to note that since the Space Station Freedom program is currently at the critical design review stage for its systems, considerable cost savings must be found in simplified or existing designs to offset the cost of changing the new systems.

During the development of the design concepts there was discussion among the teams in the systems areas to encourage use of innovative ideas which could be applied across the options. However, each team chose system designs that in their technical judgment, best fit their overall option design. Opportunities remain to transfer one option system design concept to another.

All design options predominantly draw from Space Station Freedom and Space Shuttle systems. Simplifications in these systems were sought to reduce unnecessary functionality or design inefficiency.

Differences in systems between options are shown in Appendix D. Systems are described in more detail in the individual Option A, B and C sections of this report.

Power Capabilities

Each option provides the power system capabilities in their section.

A common set of ground rules was created and used to calculate the performance of each of the options. The unique configuration and architecture of each option was modeled. All the calculations were made by a single group of individuals using the Station Power Analysis for Capability Evaluation code. All calculations were performed for a point in time after five years of on-orbit life. The calculations for the source capabilities were performed using the best estimate of performance of each component. The source capabilities reported are the best expected from each option.

The power capabilities reported are total aggregate capabilities. Whether or not the power can actually be consumed is dependent on specifics such as buss loading the ability to balance buss loading, and the amount of overhead capacity retained by the operators of the Space Station.

The source capability varies throughout the year due to orbital mechanics considerations. An example of this variation is presented in Figure 3 and Figure 4. Figure 3 represents the time variation of the available power for one Option B configuration for a 28.8 degree inclination orbit. Figure 4 is the same representation for a 51.6 degree inclination orbit. Figures presented in the Option A section illustrate that operational considerations can also impact the source capability.

Two standard measures of performance have been selected, The first measure is the average power available during a single orbit that has the yearly average shade duration. On Figure 3 this standard orbit is typified by day 350. On Figure 4 the standard orbit is typified by day 50. The performance differs in sunlight and eclipse in these examples due to an excess of array capacity relative to battery capacity. A weighted average of the sunlight and eclipse performance is the number used in this report by all options. At a 28.8 degree inclination the number is close to an annual average. This measure tends to overestimate the power available in a 51.6 degree inclination orbit.

The second measure is the greatest amount of power that can be delivered for a 30 day con-

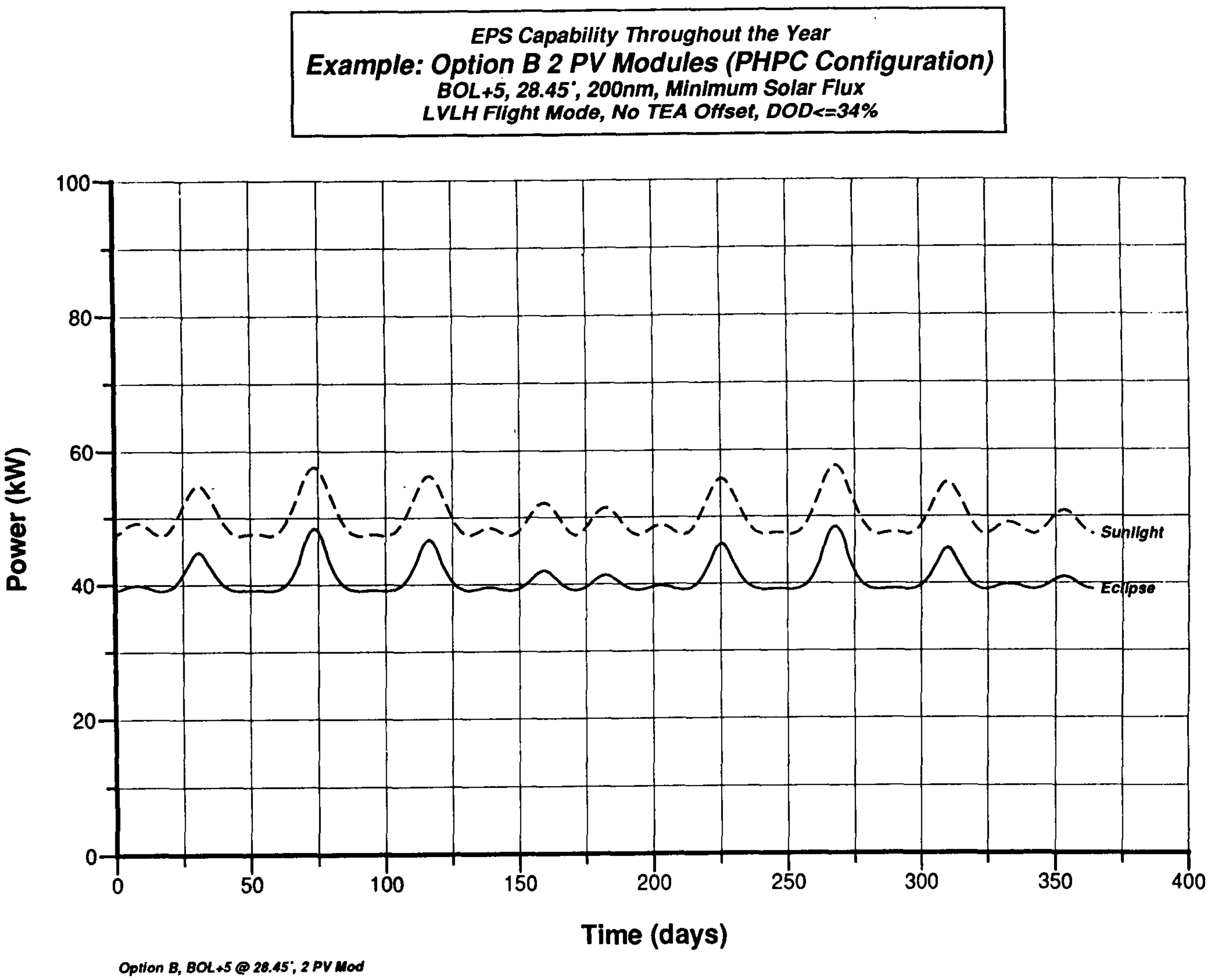


Figure 3
Option B two photovoltaic modules

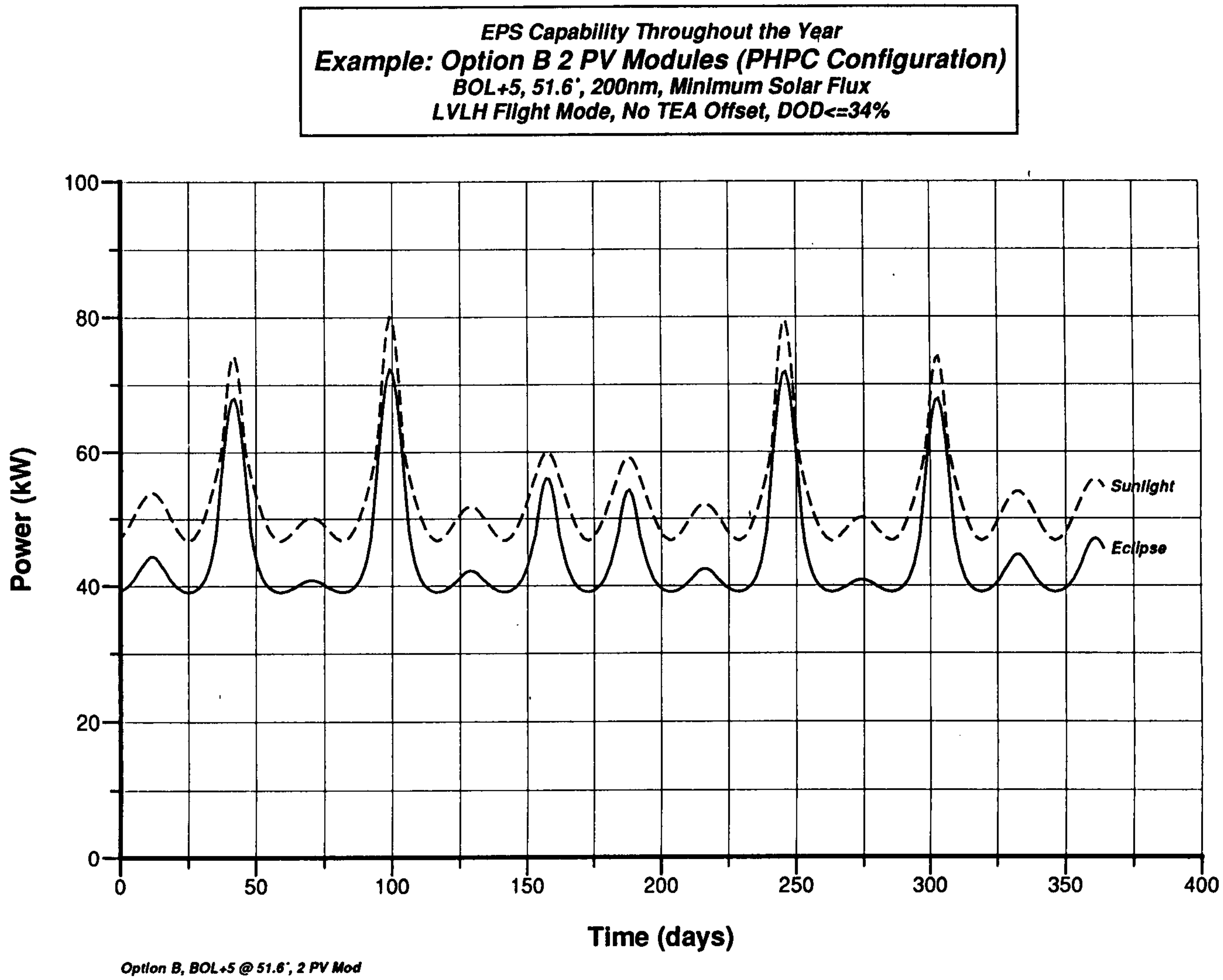


Figure 4
Option B two photovoltaic modules

tinuous period. This number is very close to the bottoms of the performance curves shown in Figures 3 and 4. Due to orbital mechanics considerations, this measure does not change with orbit inclination.

Each option has presented these "standard measures" of the performance. In addition to these standard measures, Option A and Option B have included additional information.

Option A has also presented the power capability as a time phased translation of the Space Station Freedom power requirement; i.e., the amount of power available at each assembly stage if the power system just meets the requirement. The power system performance degrades slowly over time. The time phased capabilities should be greater than the five year numbers used in the standard measure. However, the power system is exceeding the requirement. Therefore, the time phased numbers under report the capability relative to the standard measures.

Option B has also reported an annual average capability. This is obtained by averaging the capabilities shown in Figures 3 and 4 over an entire year. At a 51.6 degree inclination the capacity peaks can influence this average.

Resource Margins

In spacecraft design, it is important to maintain reserves in resources, including mass and power. During this exercise, it was particularly important to maintain margins in mass as new concepts or changes to concepts were contemplated. The design support teams managed their own reserves using standard approaches.

In assembling the Space Station using the Space Shuttle, a 3,500 pound margin for each flight was maintained as a Space Shuttle manager's reserve. A 1,800 pound Space Station program manager's reserve also was maintained. These mass margins are consistent with those currently maintained in Space Shuttle and Space Station Freedom programs. In addition, mass margins were kept for individual items and systems, and the margins varied according to the degree of development of the particular system. Mass margins at critical design review in the Space Station Freedom program were kept at 10 percent. New designs were kept at 20 to 25 percent. Existing off-the-shelf equipment carried no reserve. For example, consider the use of existing Space Shuttle systems in Option C. If modifications were made, a margin of 5 to 10 percent was applied, depending on the magnitude of the change. A 15 to 25 percent mass margin was applied to new vehicle structure.

Calculations for the electric power system source capabilities were performed using the best performance of each component. All calculations were performed by the same members of the Redesign Team using consistent groundrules and option specific architectures. No margin was retained for the source. The source capabilities reported were the best expected for each option at beginning of life plus five years. Margins were kept for the system loads, according to the level of knowledge of the systems as they relate to the power system. All options kept five percent reserves for Space Station equipment loads and Option C kept zero percent for Space Shuttle equipment loads. Table 7 summarizes the reserves discussed.

Cost and schedule reserves for each option were also calculated and are reported in the cost section.

Transportation

Introduction

The Space Shuttle serves as the baseline transportation system for all the options considered by the Station Redesign Team. Alternative trans-

Table 7
Reserves

Option	Power Load	New Equipment	Mass margins Space Station Freedom	Existing Equipment
A1	10%	20%	5-10%	0%
A2	10%	20%	5-10%	N/A
B	5%	N/A	10%	N/A
C	0%-Space Shuttle, 10%-Space Station Freedom 10%-New Equipment	20%	10%	0-10%

portation options were examined for the Space Station assembly sequence and the on-orbit delivery of both crew members and logistical support elements. Currently, only the Space Shuttle and the Russian Soyuz launch vehicle are human rated for crew delivery. The Russian Proton launch vehicle and the Ariane 5, currently being developed by the European Space Agency, are being considered for human rating. Cargo transportation options include domestic and international launch vehicles and transfer stages.

Space Shuttle

Use of the Space Shuttle includes not only the Space Shuttle vehicle but the supporting ground and flight operations infrastructure. Options A and B use the Space Shuttle for assembly, utilization and logistic flights. Option C utilizes Space Shuttle system elements to create a modified launch vehicle to deliver the core station to orbit in a single launch. This is followed by regular Space Shuttle flights for outfitting, utilization logistics and delivery of the international elements.

The Space Shuttle, with its crew and mission support equipment inventory, provides a high degree of flexibility for station assembly and operation. The capability of the Space Shuttle varies depending on many factors including orbital destination, cargo configuration, crew size and a number of other variables. The nominal Space Shuttle performance to a 220 nautical mile circular orbit is:

	Orbital Inclination	
	28.8 degrees	**51.6 degrees**
First element launch (no rendezvous)	39,700 lbs.	27,400 lbs.
Subsequent launches (rendezvous)	37,800 lbs.	25,000 lbs.

Key ground rules for these capabilities are:

- Five person crew
- Seven day mission duration
- Remote manipulator system installed
- No planned extravehicular activity
- Space Shuttle main engine improvements included
- Capabilities must be reduced for payload integration items and for airlocks and docking requirements in pressurized and unpressurized docking modes.

The baseline Space Shuttle flight rate is assumed to be eight per year. The maximum crew duration prior to Space Station permanent human capability is 20 days. This 20 day capability is to be demonstrated by January 1, 1998. The crew duration will be extended incrementally after sufficient confidence is gained in crew performance after 20 day durations.

In addition to the planned improvements in the Space Shuttle main engines, further planned and potential improvements to the Space Shuttle include the advanced solid rocket motor, the aluminum lithium external tank and the long-duration orbiter. Additional modifications to the overall Space Shuttle system, as required, are noted in the description of the three options.

The advanced solid rocket motor is a design upgrade to the solid rocket motors used in the current Space Shuttle configuration. Use of the advanced solid rocket motor eventually results in a 12,000 pound improvement in Space Shuttle payload capability. With funding in the fiscal year 1994 congressional budget, the first Space Shuttle launch using advanced solid rocket motors will be in December 2000. The first two flights of the advanced solid rocket motor will be test flights where the allowable performance improvement will be limited to 8,000 pounds. There will then be eight flights with a 10,000 pound performance allowance before the 12,000 pound improvement can be entirely used. Additional funding could accelerate the first launch by two years.

The current Space Shuttle external tank uses aluminum 2219 as its primary structural material. The proposed aluminum lithium tank uses the alloy aluminum lithium 2195 which is superior to aluminum 2219 in strength, stiffness and density. Use of aluminum lithium along with modest design changes in the tank, result in an overall weight savings of approximately 7,500 pounds. This equates to a 7,500 pound improvement in Space Shuttle payload capability. Given authority to proceed with the aluminum lithium tank program in October 1993, first launch is planned for November 1997. Although the material change will affect the external tank stiffness, the resulting interface loads remain approximately the same and since there are no aerodynamic changes with this modification, a test flight will not be required and the full 7,500 pound performance improvement will be available on the first flight.

The long-duration orbiter activity is a series of system, avionics and software upgrades to the orbiter to give it the capability to remain on orbit for up to 28 days and have the potential to increase this stay-time to 60 to 90 days. This program is a direct follow-on to the current extended duration orbiter program which will extend orbit stay-time from the current 7 to 10 day baseline up to 16 days. The primary factors affecting 60 to 90 day stay-times are systems reliability, consumables limitations and crew physiology concerns. There will be a build-up program to certify crew physiological performance beyond today's fourteen day limit. For purposes of this study, twenty days was used for human tended Space Station flights, although it is anticipated that crew stay-times will go beyond that, and may in fact be superseded by other limitations (for example: crew provision stowage). Should the human tended phase be a stopping point, consideration will have to be given to the use of autoland return of long-duration crews, or an exchange of pilots using dual orbiter operations.

Alternative Transportation Options

Introduction

The Station Redesign Team examined a variety of transportation options for delivery of humans and cargo as an alternative to the Space Shuttle. These options are discussed in more detail in Appendix E. Expendable launch vehicle options for cargo delivery range from use of Titan IV as a launch vehicle for first element launch to consideration of other United States, International Partner and Russian launch vehicles and transfer stages for delivery of assembly elements and logistics. The primary focus of the assessment was for logistics cargo delivery. However, delivery of the international pressurized modules (Japanese Experiment Module and the Columbus Attached Pressurized Module) to high inclinations, was also assessed. United States and International Partner expendable launch vehicle access to a Space Station at any inclination from 28.8 degrees to 51.6 degrees is possible without a significant effect on payload delivery capability. Consideration of Russian transportation participation will influence the strategy for the choice of the Space Station inclination. Figure 5 depicts the options for access to the Space Station, and Figure 6 illustrates the alternative vehicles.

United States Expendable Launch Vehicles

All United States expendable launch vehicles would launch from the Cape Canaveral Air Force Station in Florida (latitude 28.6 degrees North). The Delta II with a modified upper stage could perform some small class logistics missions. Atlas IIAS, Titan III and Titan IV could, in principle, deliver a Russian Progress resupply craft or a Soyuz assured crew return vehicle. Currently there is no transfer stage for use in delivering Space Station hardware on United States expendable launch vehicles, however.

Titan IV could be used for a first element launch for Options A and B where a transfer stage is not required (no rendezvous). However, the Titan IV is not cost effective to NASA for limited application.

International Partner Launch Vehicles

The European Ariane 44L (largest version of the Ariane 4 family) and planned Ariane 5 vehicles have the potential to deliver the Progress resupply craft, the Soyuz assured crew return vehicle or a future European assured crew return vehicle for all inclinations from 28.8 degrees to 51.6 degrees. The Ariane 5, scheduled for its first flight in 1995, is being designed to carry its own automated transfer vehicle which could also be used to deliver assembly or logistics elements. In addition, the Ariane 5 is designed to be human-rated and could potentially be used for human access to Space Station. The smaller Ariane 4 could also deliver the Progress but is planned to be phased out in 1999. The European vehicles launch from the Guiana Space Center near Kourou, French Guiana (latitude 5.2 degrees North).

The Japanese H-II could be used to launch Progress resupply craft to inclinations from 28.8 degrees to 51.6 degrees and is not intended to be human-rated. The H-II is launched from the Tanegashima Space Center (latitude 30.2 degrees North).

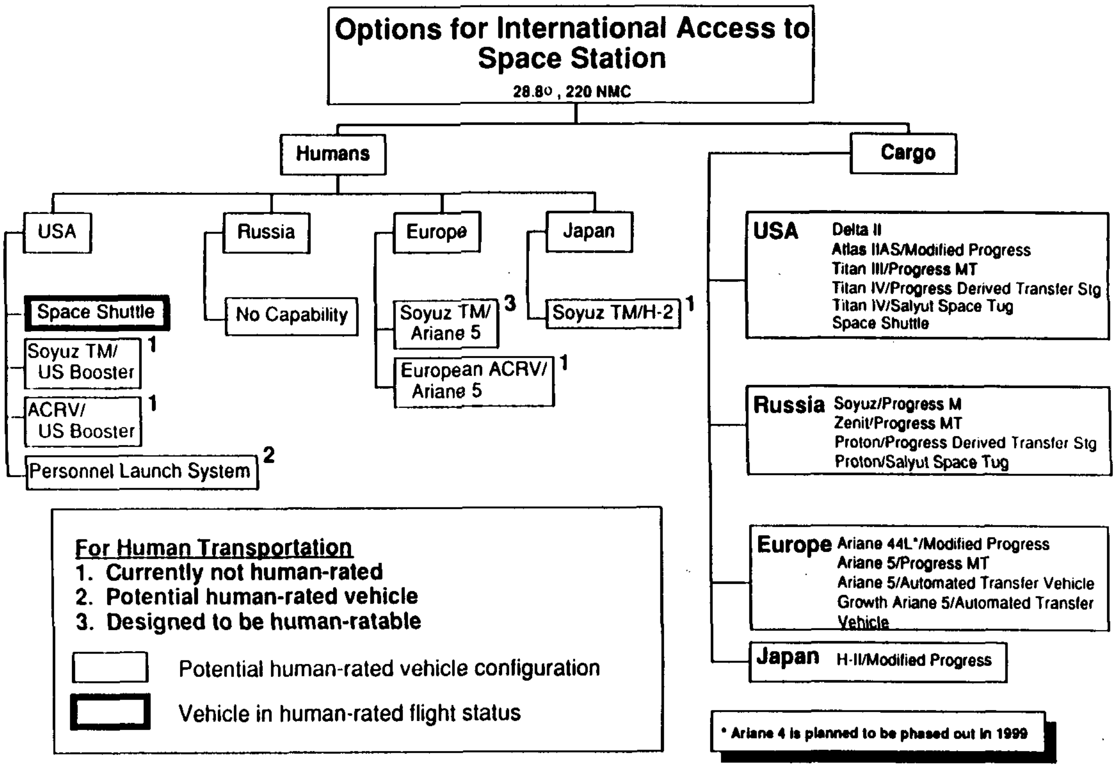


Figure 5
Options for international access to Space Station

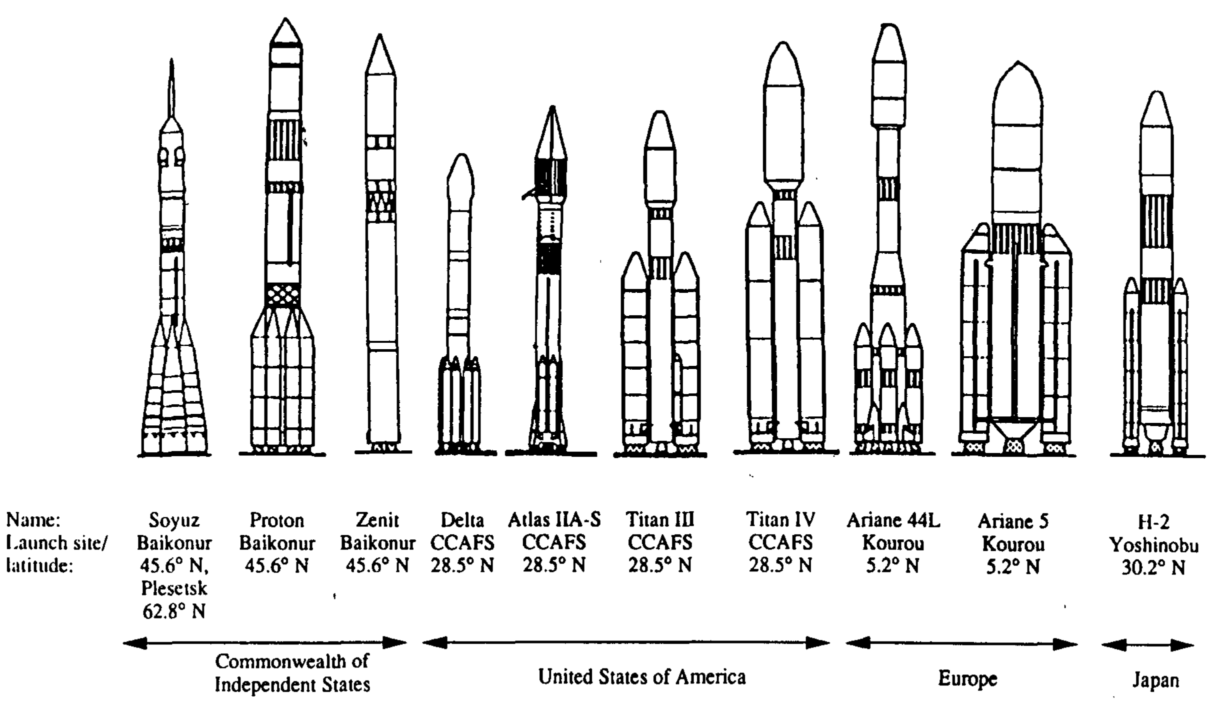


Figure 6
International expendable launch vehicles

Russian Launch Vehicles

The launch vehicles considered include the Soyuz booster, Proton and Zenit. The Soyuz booster is the only human-rated Russian launch vehicle. Because of launch site and performance limitations, it is only capable of delivering the Soyuz TM or Progress resupply craft to an inclination of 51.6 degrees for human or cargo delivery, respectively. The Zenit was designed as a potential replacement for the Soyuz booster for transporting Russian crews to orbit via the Soyuz TM and is thereby human-ratable. It is also capable of Progress resupply craft delivery. As with the Soyuz booster, however, the Zenit capability is currently limited to inclinations near 51.6 degrees.

The Proton has been Russia's primary heavy lift launch vehicle since the late 1960s. It offers significant potential to Space Station options utilizing higher orbital inclinations. The Proton could deliver Space Station assembly elements or large logistics payloads of up to 38,500 pounds to 220 nautical miles at a 51.6 degree inclination. It is also capable of delivering Progress vehicles or a Soyuz assured crew return vehicle to inclinations as low as 33 degrees. The Proton is not currently human-rated. More details on the Proton vehicle are discussed in Appendix E.

The Russian vehicles would launch from the Baikonur Cosmodrome in Kazakhstan (latitude 45.6 degrees North) in support of Space Station.

Summary

The Space Shuttle and the Soyuz TM are the only currently available human-rated systems for access to the Space Station. The Space Shuttle can deliver humans to inclinations from 28.8 degrees to 51.6 degrees with varying payload capability depending on the configuration employed. The Soyuz TM delivered to orbit by the Soyuz booster is limited to 51.6 degrees due to booster capability and range safety limitations. Other options for human access to the Space Station via the Soyuz TM, an assured crew return vehicle or other crewed vehicle (e.g., a personnel launch system) would require human-rating of an expendable launch vehicle, although Ariane 5 and Zenit are designed to be human-ratable.

The United States and International Partner expendable launch vehicle fleets have access to the full inclination range. For these vehicles, capabilities are relatively insensitive to the different inclination. However, a transfer vehicle capability must be developed. This capability could be an adaptation of an existing Russian transfer vehicle (e.g., Progress M) or some variant, a new vehicle (e.g., the automated transfer vehicle), or the modification of a current expendable launch vehicle upper stage or injection stage.

Russia has a set of launch vehicle and spacecraft assets that has proven to be both reliable and capable. With some modification to the redesigned Space Station options, these launch systems could be applied, to varying degrees, to achieve multiple human and cargo access to the Space Station if it is located at an inclination above approximately 33 degrees. To make the full potential of Russian systems available, the Space Station must be assembled at an inclination very near 51.6 degrees and be designed to accommodate an approaching expendable launch vehicle payload. Such an accommodation would enable multiple access from other nations and would enable a Proton contribution to the assembly sequence as well.

Option A

Introduction

Option A is a modular concept responsive to the overall Space Station redesign requirements, while emphasizing programmatic and design solutions that result in a reduced size and cost station. The Option A concept concentrates on program approaches that offer significant management, design and operations cost reduction options for a Space Station while focusing on maintaining key science and research capabilities, international commitments and other objectives. Two very similar and viable options have been defined. Either option offers good user responsiveness as it builds toward permanent human presence, and either is capable of stopping at any of three intermediate capability levels. Both options are discussed in this report.

Option Specific Requirements, Guidelines and Constraints

A major design consideration on Option A is to provide a modular buildup approach that, while keeping a strong focus on user needs and international agreements, also provides a lower cost approach to Space Station. The modular buildup approach incorporates four buildup phases. Phase 1 is a Power Station to which payloads or a Space Shuttle and Spacelab could attach. Phase 2 is a Human Tended Capability which adds a pressurized laboratory with docking ports and some international equipment. Phase 3 is an International Human Tended Capability attained with the addition of the two international laboratory modules and other equipment. Phase 4 is a Permanent Human Capability achieved by addition of other elements. If cost constraints limit the capability of the Space Station, it could be optimized for improved performance at any of the four phases. The most efficient and effective operations are attained at Permanent Human Capability, which is a primary goal.

A key guideline is to use current and simplified Space Station Freedom systems where cost-effective, and to repackage, and simplify elements to reduce overall costs, assembly flights and extravehicular activity. Existing systems are to be considered where practical. Specifically, the Lockheed Bus-1 spacecraft was assessed for guidance, navigation, control and propulsion. Selected Space Shuttle and Spacelab systems, Russian systems, and limited commercial hardware were also assessed and incorporated.

Option A deployment and assembly begins in October 1997, with a buildup to Permanent Human Capability. Orbiter visits to the Space Station during the buildup time frame are limited to 16–20 days duration. In the Permanent Human Capability phase, orbiter visits are intentionally kept shorter (seven days). The orbiter uses power from the Space Station in the first three phases. Utilization flights are interspersed with assembly flights in the buildup sequence to enhance early payload operation. Some utilization flights include partial complements of logistics or other equipment, but each is primarily payload-related.

Alternative orbital inclinations (28.8 degrees to 51.6 degrees) were investigated. Major emphasis in the Option A report deals with 28.8 degree inclination, with implications summarized on other inclinations.

Description of Concept

External Configuration

Overall Configuration and Capability Levels

Option A includes two very similar options, Option A-1 with a Bus-1 spacecraft and Option A-2 without the Bus-1. Either option builds toward permanent human presence, and either is capable of stopping at any of three intermediate capability levels. Figures 7 and 8 reflect this launch and buildup strategy for the 28.8 degree inclination and the resulting configuration capability levels. Option A-1 and Option A-2 are compared to the Space Station Freedom in Figure 9, which shows the overall configuration and element differences among the options.

Both Option A approaches are considered evolutionary. The configurations at the four capability levels are shown in Figures 10 and 11 for Option A-1, and in Figures 12 and 13 for Option A-2. For both options, the Power Station is established after three assembly flights and includes power generation (20 kW), thermal control, avionics and attitude maintenance capability. Human Tended Capability adds a common core-laboratory with multiple docking ports, and is achieved after four assembly flights. The Canadian Space Agency's Space Station Remote

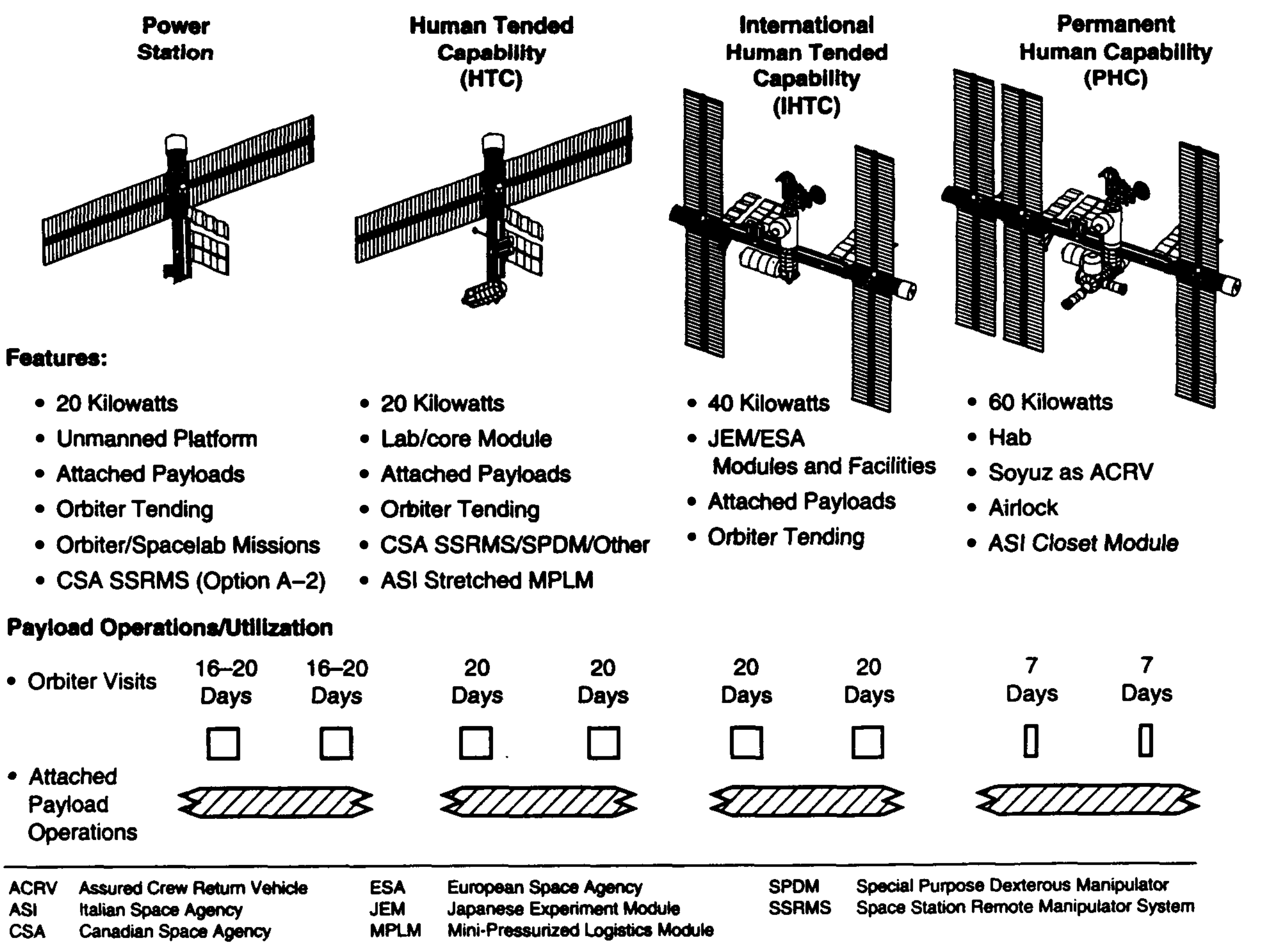
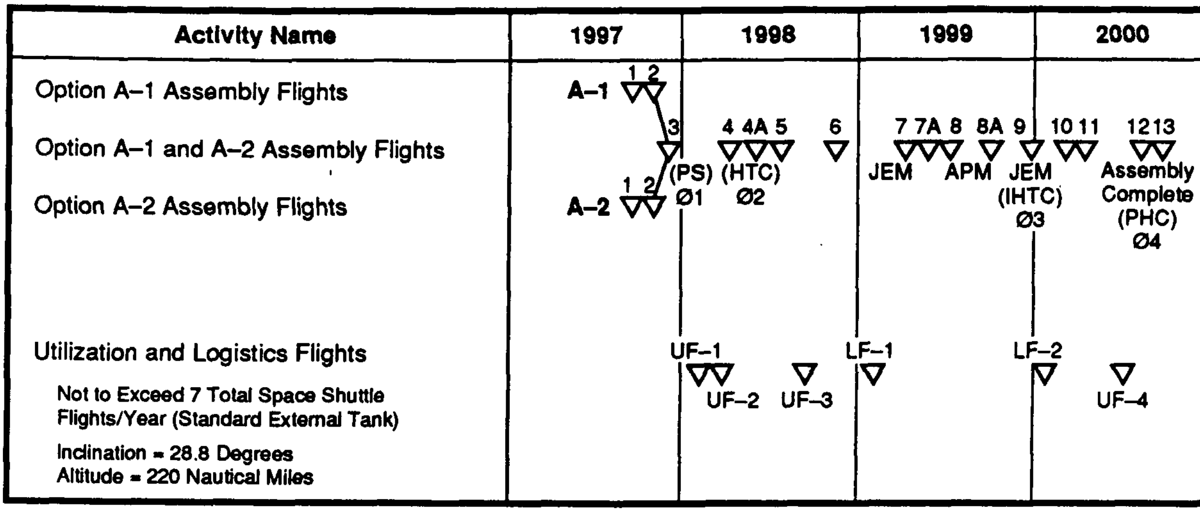


Figure 7
Modular buildup Space Station phases and potential stop capability points



APM	Attached Pressurized Module	LF	Logistics Flight
HTC	Human Tended Capability	PHC	Permanent Human Capability
IHTC	International Human Tended Capability	PS	Power Station (Early Research)
JEM	Japanese Experiment Module	UF	Utilization Flight

Figure 8
Assembly strategy

Manipulator System is delivered in Phase 1 (Option A-2), and the Canadian Mobile Servicing System is completely operational in Phase 2 for both options. The proposed Italian stretched mini-pressurized logistics module begins operation in Phase 2. International Human Tended Capability occurs after 12 assembly flights. During this phase additional power generation (40 kW total), additional thermal control, a cupola, the Japanese Experiment Module, the Columbus Attached Pressurized Module and the Japanese Experiment Module Exposed Facility, Experiment Logistics Module and Exposed Section are added. Permanent Human Capability, which is attained after 16 assembly flights, provides additional power generation (60 kW total), a common habitation module (crew habitability with additional docking ports), an airlock, a closet module derived from the mini-pressurized logistics module, and two Russian Soyuz vehicles that serve as assured crew return vehicles.

The general arrangement for Option A-1 and Option A-2 is similar, but there is a 90 degree difference between Option A-1 and Option A-2 in the relative orientations of the truss faces and deployed arrays. Either option could be configured either way. The relative orientation of the solar array and the central truss on Option A-2 is driven by the power system and first truss section being mated prior to launch. Option A-1 requires less inboard truss than Option A-2 since it does not have attached propulsion modules, but it does require a new transition section. This new transition section allows the inboard and outboard radiators to be aligned. The module pattern for both options is driven strongly by clearance for the Space Shuttle Remote Manipulator System during assembly, and by payload viewing requirements.

The overall dimensions at Permanent Human Capability, with the third set of solar arrays for Option A-1, are 245 feet overall length and solar array tip-to-tip length of 248 feet, and for Option A-2 are 281 feet overall length and a solar array tip to tip length of 248 feet. These overall lengths are 75 feet to 110 feet shorter than Space Station Freedom's 355 feet. The on-orbit mass at each phase is shown in Figures 10 through 13.

Design Elements

Major changes from Space Station Freedom include deletion of some truss sections (five in

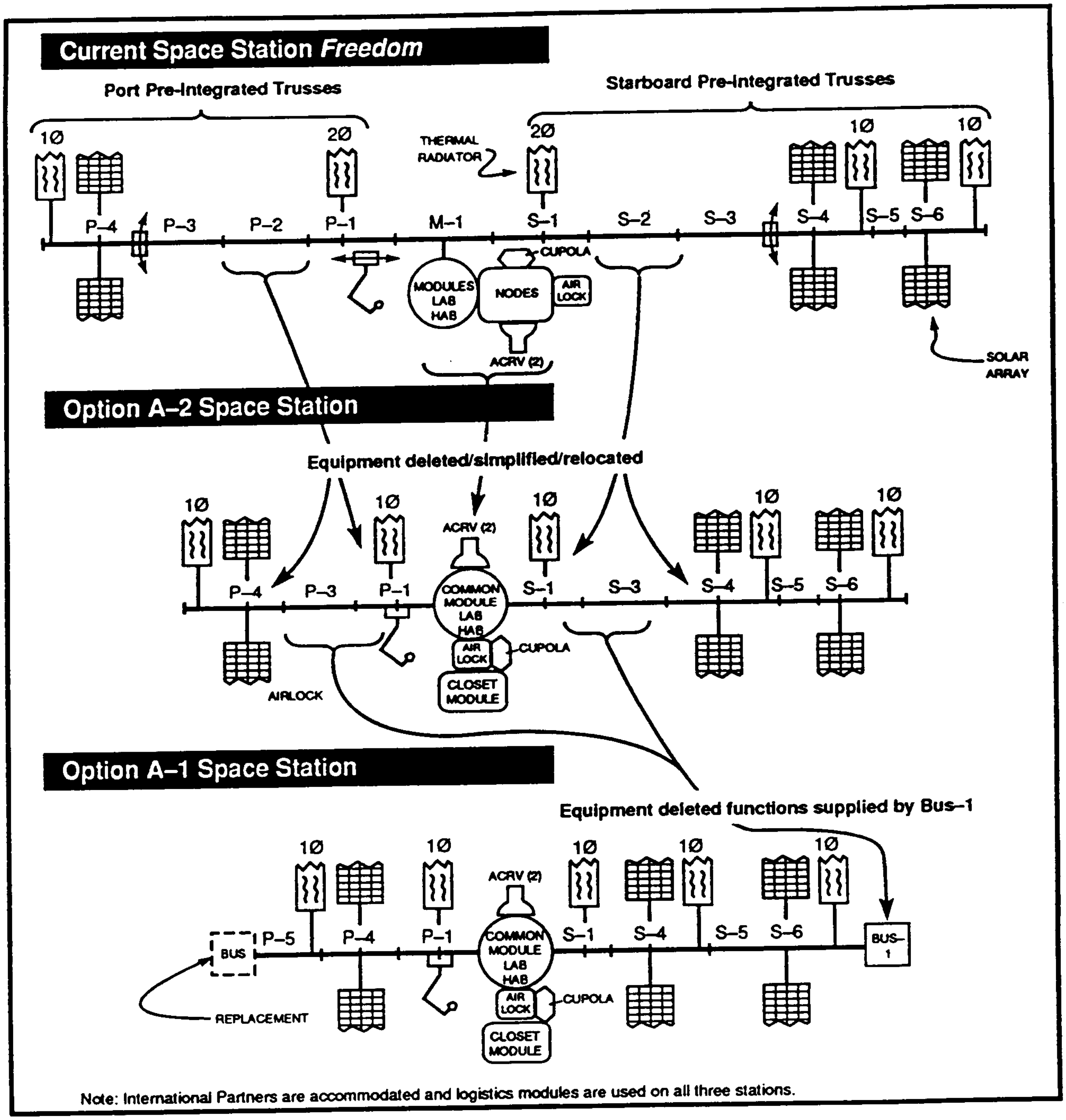


Figure 9
Space Station configurations

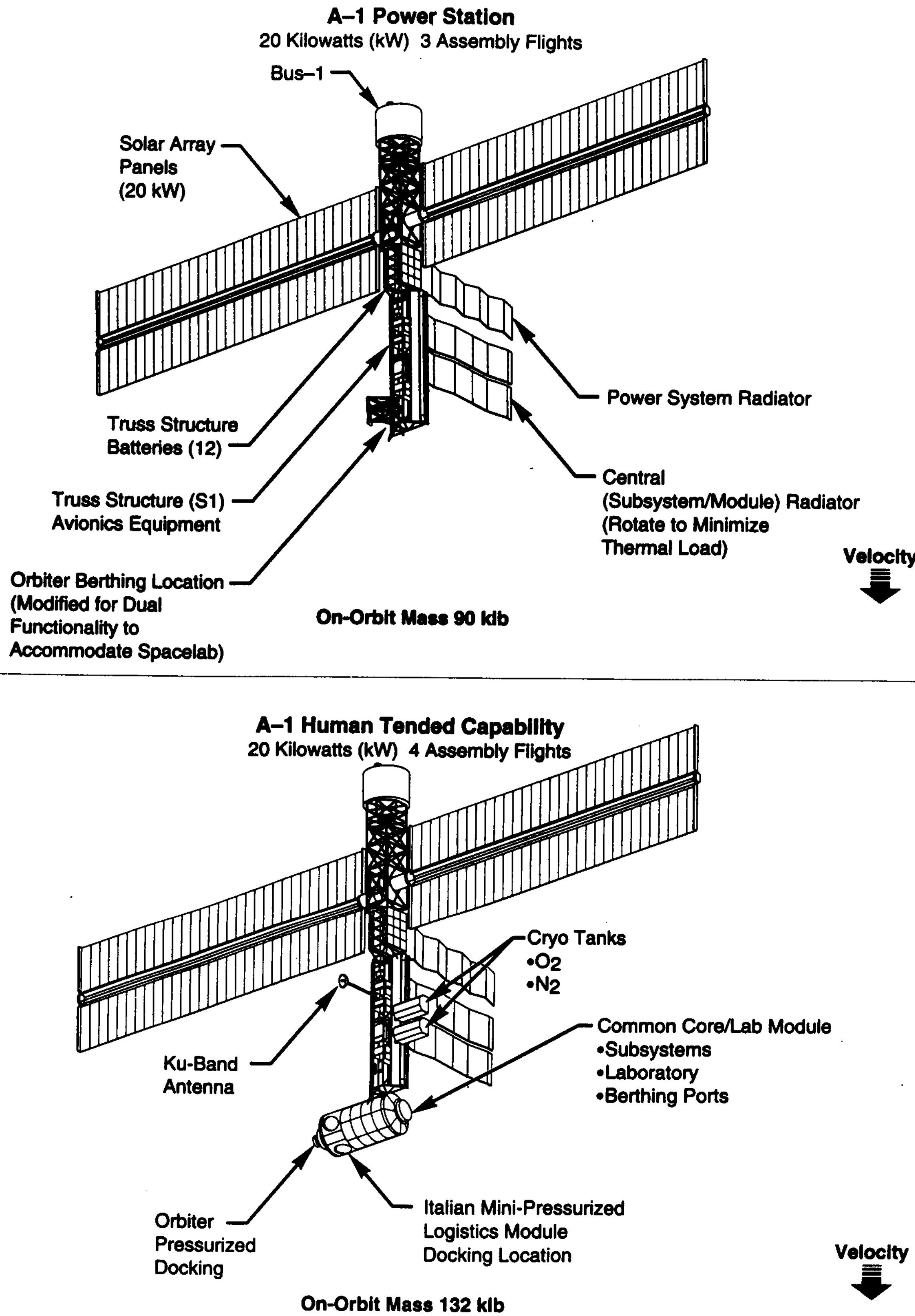
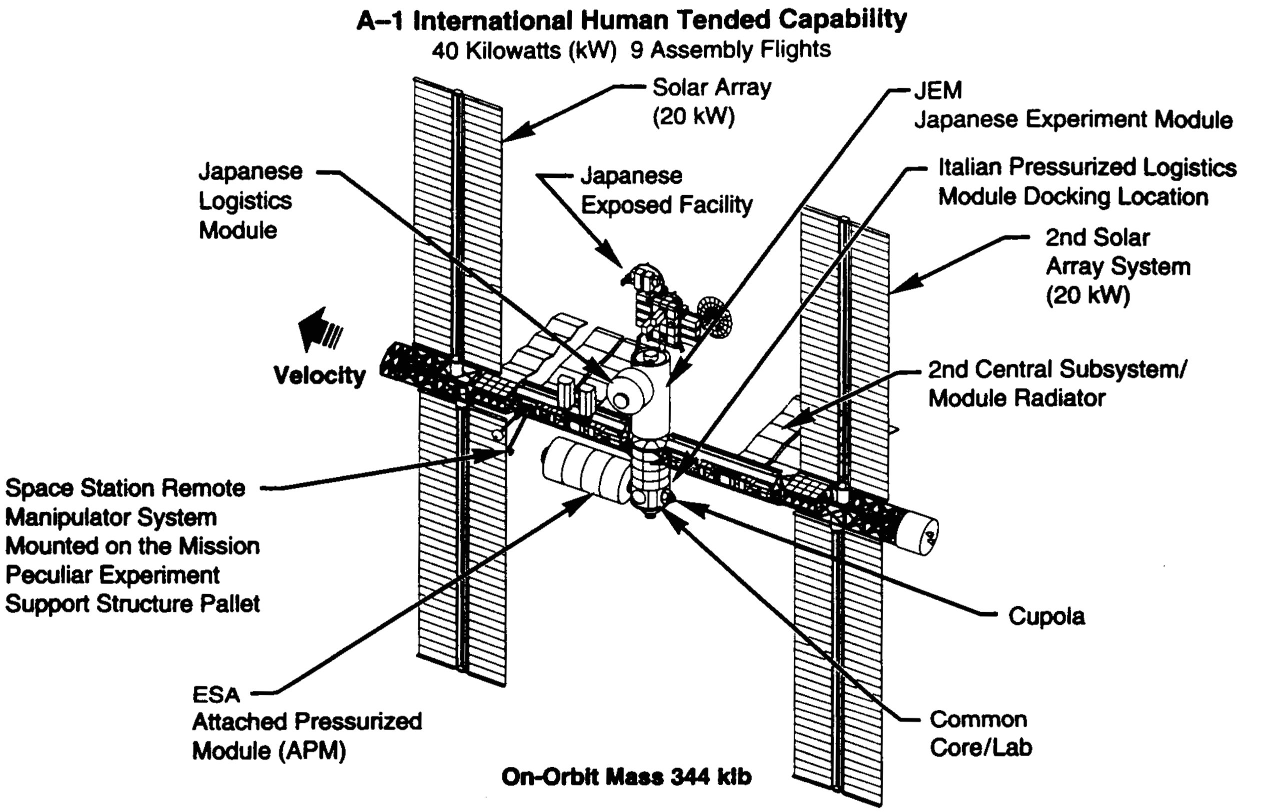


Figure 10
Option A-1 (with Bus-1) Power Station and Human Tended Capability



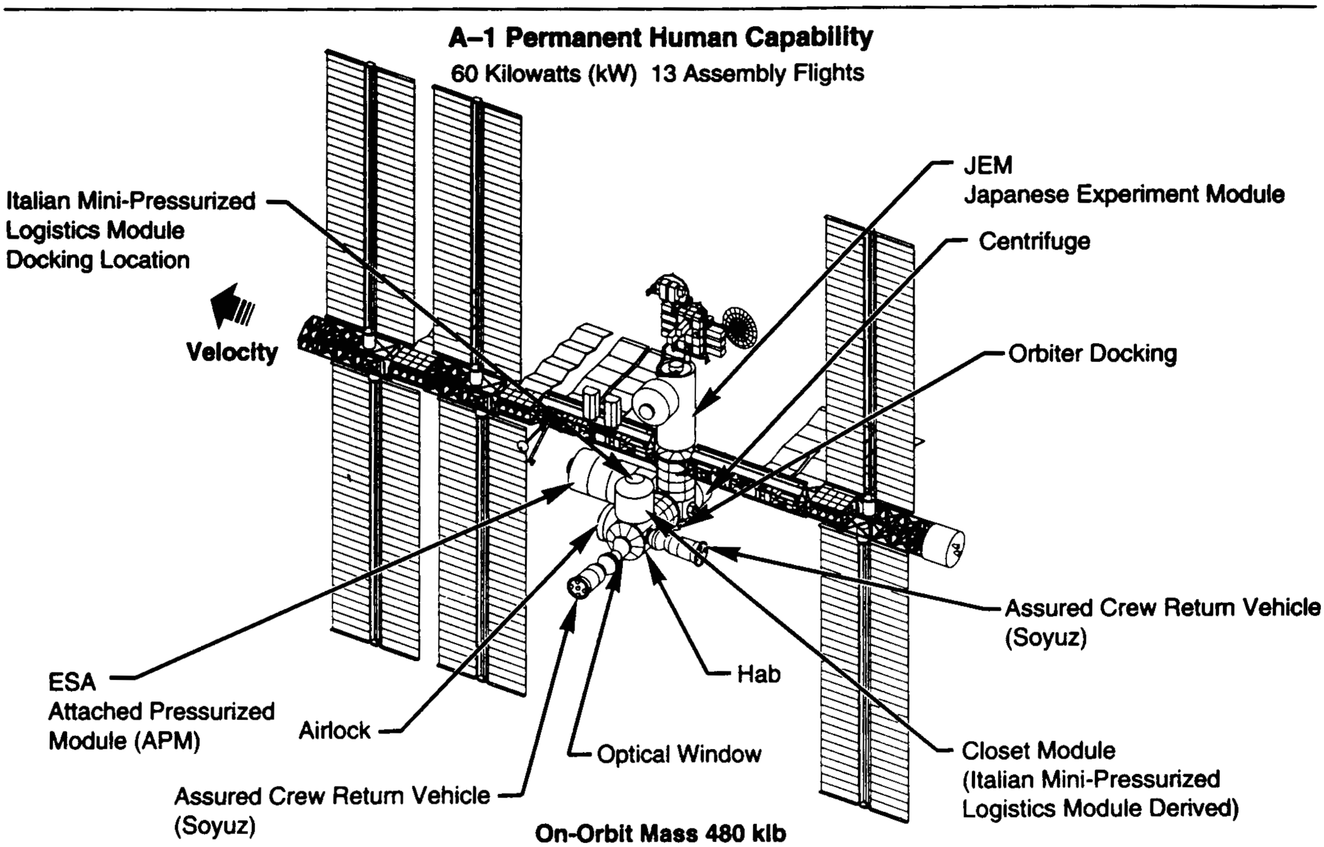
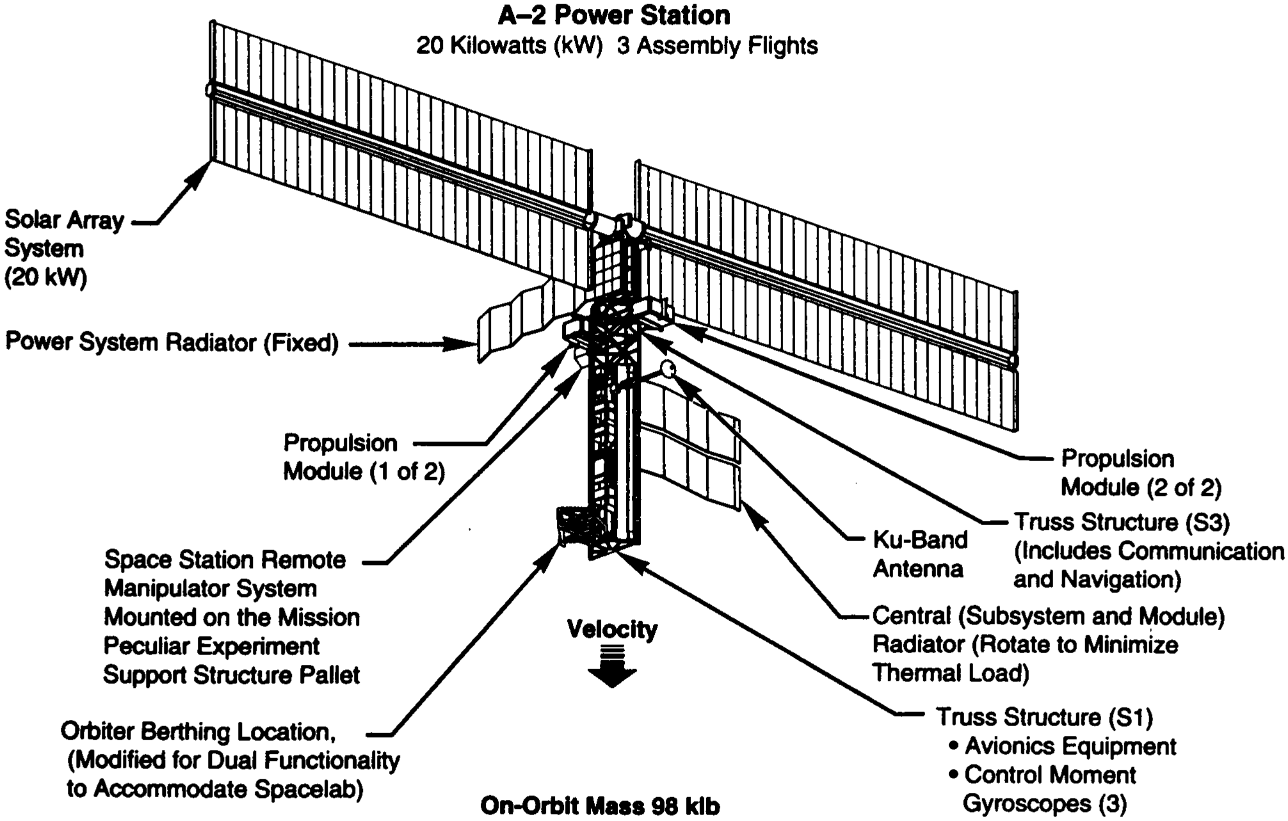


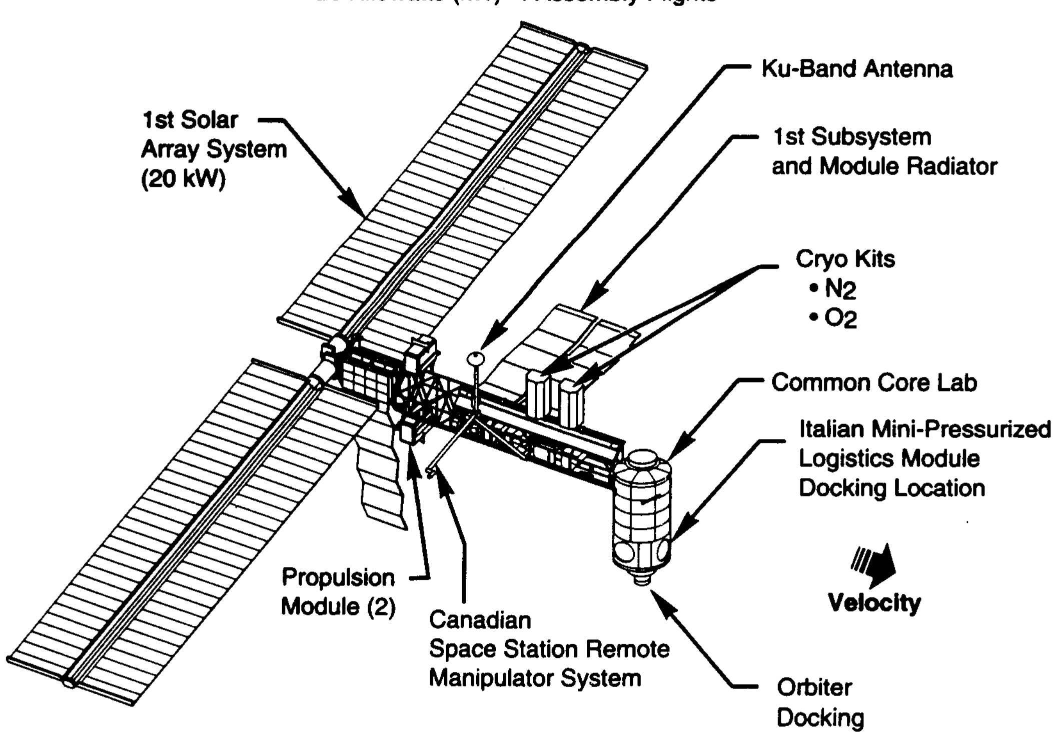
Figure 11
Option A-1 (with Bus-1) International Human Tended and Permanent Human Capabilities

A–2 Power Station
20 Kilowatts (kW) 3 Assembly Flights



On-Orbit Mass 98 klb

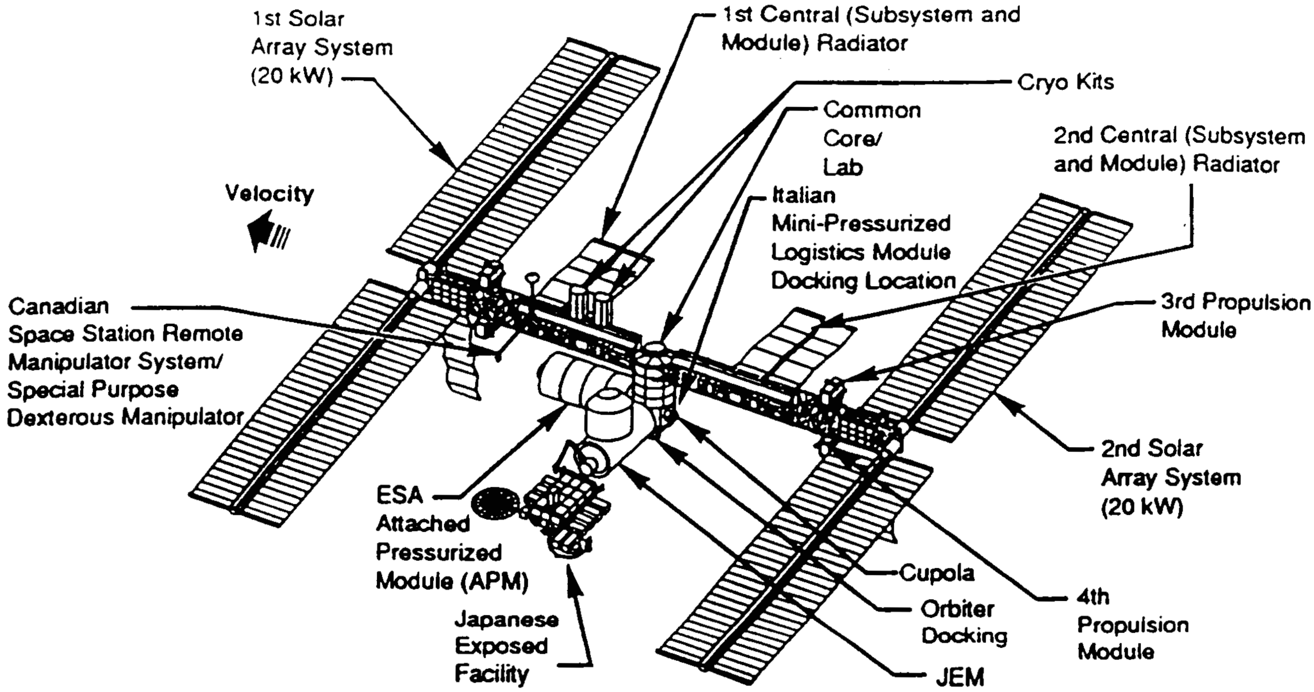
A–2 Human Tended
20 Kilowatts (kW) 4 Assembly Flights



On-Orbit Mass 140 klb

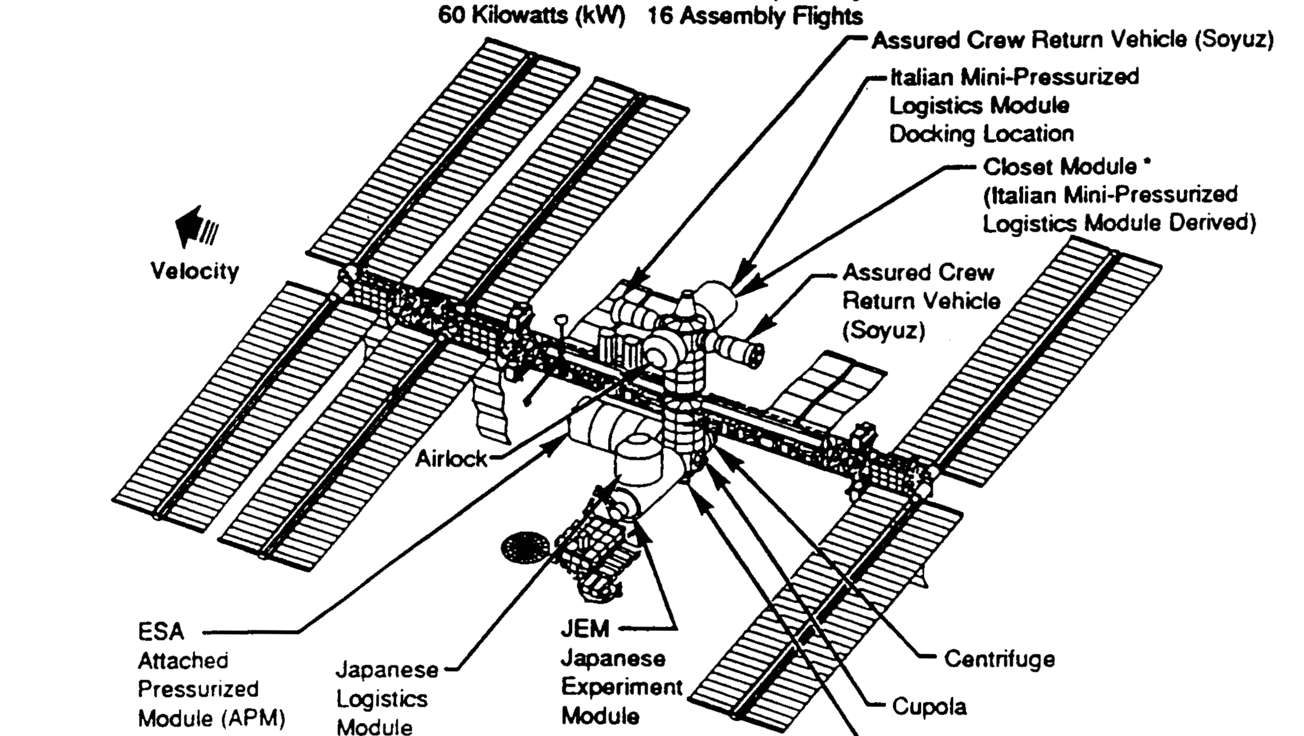
Figure 12
Option A-2 (without Bus-1) Power Station and Human Tended Capability

A–2 International Human Tended Capability
40 Kilowatts (kW) 12 Assembly Flights



On-Orbit Mass 354 klb

A–2 Permanent Human Capability
60 Kilowatts (kW) 16 Assembly Flights



On-Orbit Mass 488 klb

* Optical-Quality Window in Hatch

Figure 13
Option A-2 (without Bus-1) International Human Tended and Permanent Human Capabilities

Option A-1 and three in Option A-2), use of common modules rather than nodes plus modules, a simplified solar array and battery system, deletion of alpha rotary joints, a single-phase rather than two-phase radiator system, major simplifications in the data management and associated software, a simplified and smaller airlock (at Permanent Human Capability) derived from elements of the module, reliance on a stretched mini-pressurized logistics module with deletion of the pressurized logistics module, and a closet module derived from the mini-pressurized logistics module. A more detailed list of deletions is provided in the section of the report on Potential Cost Savings Features.

The orbiter is relied upon to provide crew systems support through the International Human Tended Capability phase, which includes the external airlock (when an orbiter is present) and selected extravehicular activity and crew support equipment. Other sources of hardware include an eight-inch optical window from Spacelab, laptop computers, some extravehicular activity tools from commercial sources, Bus-1 for Option A-1, and the use of the Russian Soyuz spacecraft as an assured crew return vehicle. Other potential uses of Russian equipment include hardware for closure of the environmental control and life support system oxygen loop and select use of docking hardware.

Stopping Points

Each phase offers reasonable capabilities for interim Space Station operation and utilization during the buildup sequence. If the configuration is frozen at one of these phases, adjustments can be made to optimize the Space Station for operation at that phase. If assembly stopped at the Power Station phase, the Space Station Remote Manipulator System (already present on Option A-2), Special Purpose Dexterous Manipulator, and payload and orbital replacement unit accommodation equipment would be added for maintenance support. A video and high-rate data communications system would be added. One external radiator and all laboratory umbilicals would be eliminated. The reboost thrusters on the propulsion module (Option A-2) would be relocated. Additional mounting locations for external payloads would be provided.

If assembly stopped at Human Tended Capability, Option A would utilize either a common core-laboratory or a United States laboratory module as configured in the Space Station Freedom program. The orbiter would be rotated 90 degrees and docked parallel to the external truss to provide improved microgravity for payloads. The Space Station Remote Manipulator System, Special Purpose Dexterous Manipulator, and payload and orbital replacement unit accommodation equipment would be added prior to completing this modified Human Tended Capability phase. Umbilicals for the international modules and the common habitation module would be deleted, and reboost thrusters on the propulsion module (Option A-2) would be relocated. There would be no resulting reduction in capability at the Human Tended Capability phase. If assembly stopped at International Human Tended Capability, the primary change would be deletion of provisions for integration of oxygen generation equipment.

Internal Configuration

The Space Station Freedom design includes two United States pressurized elements: (1) a module and (2) an interconnect node. The modules, outfitted as laboratory or habitation modules, are interconnected by nodes. Option A combines these two United States pressurized elements to form the common module, shown in Figure 14. A common module provides the function of a node and is also outfitted as a laboratory or habitation module, with a pressurized mating adapter on an axial port for orbiter mating. The common module serves as the building block for the pressurized elements comprising Option A.

The outfitted volume of the common module is reduced by one-third of a Space Station Freedom module to accommodate the addition of four radial berthing ports. Through a combination of phased mission requirements definition (e.g., definition of stowage requirements by Human Tended Capability, International Human Tended Capability and Permanent Human Capability), subsystems simplification, and elimination of equipment duplicated in the Space Station Freedom modules and nodes, the quantity of outfitting volume needed to comprise a laboratory or habitation module can be reduced by

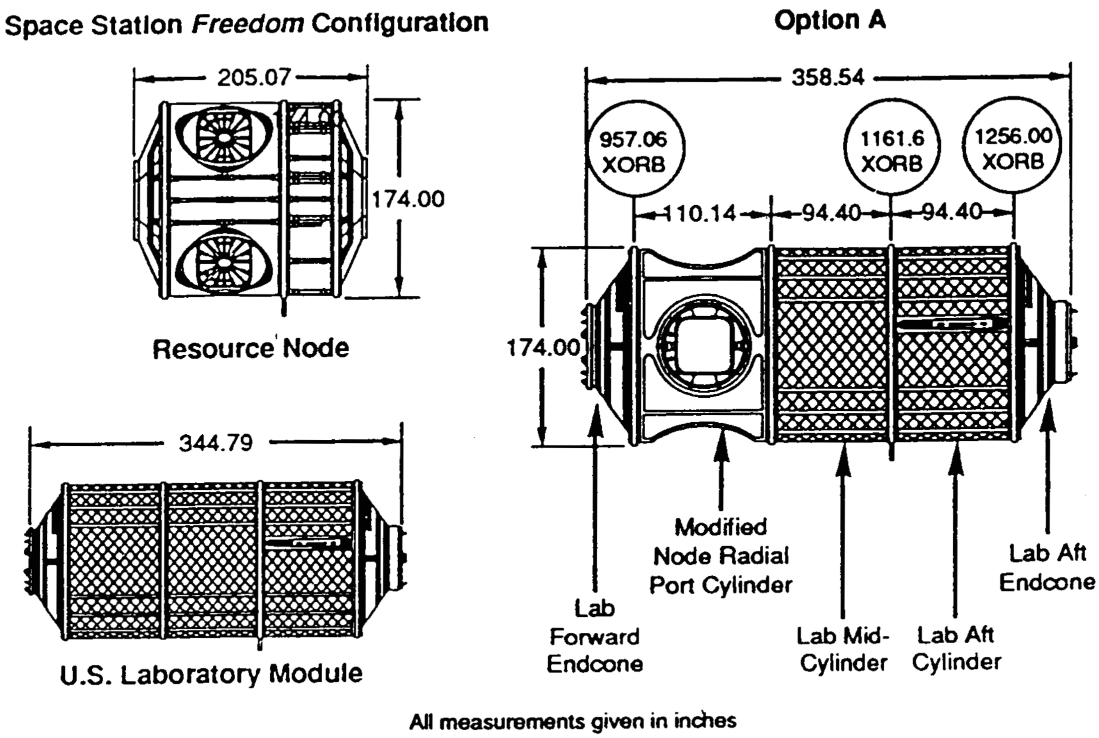
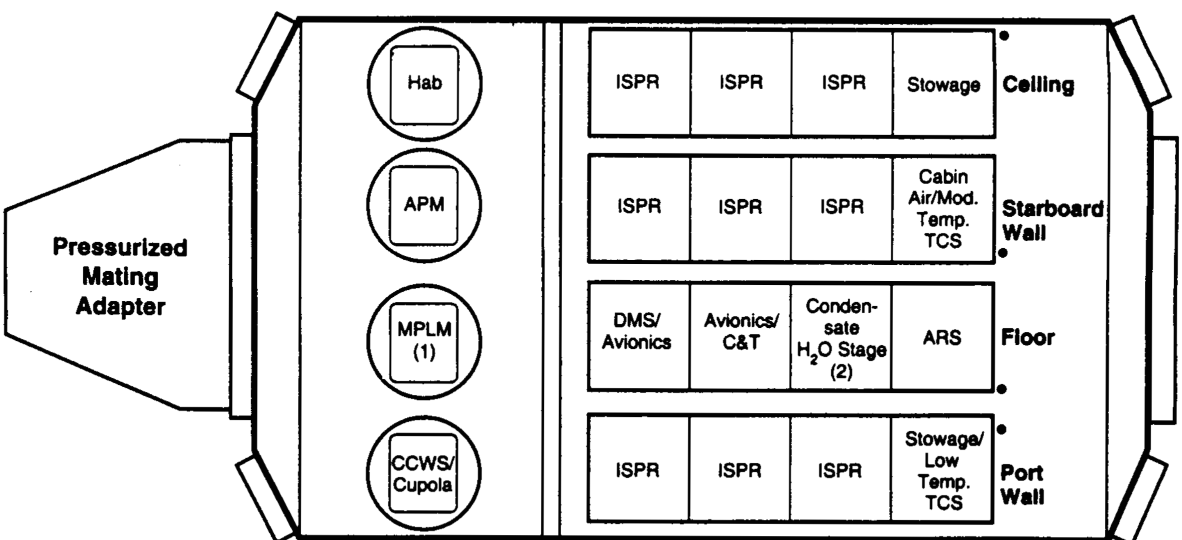


Figure 14
Common module



(1) Scarred for centrifuge laboratory
(2) Scarred for fuel cell water storage

APM	Attached pressurized module	DMS/AV	Data management system/audio visual
ARS	Atmosphere revitalization system	MPLM	Mini-Pressurized Logistics Module
CCWS	Command and control workstation	ISPR	International standard payload rack
CHeCS	Crew health-care system	TCS	Thermal control system
C&T	Communications and tracking		

Figure 15
Common core-laboratory module

approximately one-third, coincident with the outfitting volume available in a common module.

The rack-based outfitting method employed within the Space Station Freedom pressurized modules is retained within the common module. The racks are arranged in four quadrants within the cylindrical section of the module. One row of adjacent racks constitutes the floor, the opposite row forming the ceiling, and the other two rows forming port and starboard walls. This commonality with the Space Station Freedom modules allows the common module to incorporate significant portions of existing designs for the primary and secondary structure, utility routing, and rack and end cone packaging.

When outfitted as a laboratory (Figure 15), the common module provides nine rack locations for International Standard Payload Racks—three each in the ceiling and in the port and starboard walls. However, with the addition of the Japanese Experiment Module and Columbus Attached Pressurized Module, another 30 payload racks are provided; the United States allocation is 50 percent of these racks. Other racks include: stowage; atmosphere revitalization; cabin air, temperature and humidity control; condensate water storage; thermal control; and avionics (data management, audio, video, communications and electrical power). The topology is largely driven by the International Standard Payload Rack utility interface with the module; for example, providing International Standard Payload Rack utility interface plates in both floor and port wall locations would hinder service access to utility lines within that structure. Likewise, the packaging of subsystem equipment in the module end cones precludes location of an International Standard Payload Rack adjacent to the end cone. The objective was to maximize commonality with the existing design of the Space Station Freedom laboratory module.

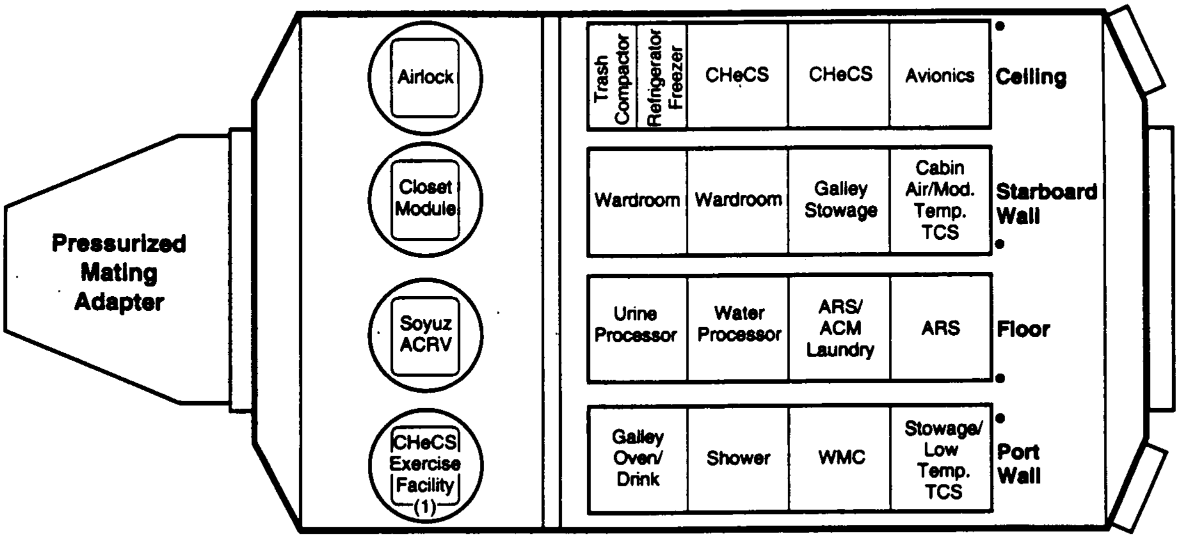
A Spacelab eight-inch diameter optical quality window is included in one hatch to allow crew viewing and Earth and sky scientific observation. At International Human Tended Capability, observation is further enhanced through addition of a cupola to the laboratory module. When the cupola is added, the robotics workstation, formerly located in an unused radial port, will be redeployed in the cupola, facilitating control of the Space Station Remote Manipulator System and the Special Purpose Dexterous Manipulator.

The common module acts as a "core" module when outfitted to provide intravehicular activity-connected resources to other modules. The common core-laboratory presently provides this core capability for the attachment of the Columbus Attached Pressurized Module. Core capability is also provided for the Japanese Experiment Module thermal system interface and thereby reduces the extravehicular activity required to mate the Japanese Experiment Module to the Space Station; however, extravehicular activity is required to connect the electrical power. Providing core capability for the electrical power interface is still under study in the Japanese Space Agency.

The topology for a common module outfitted as a habitation module is shown in Figure 16. The design will accommodate a crew of four for 90-day missions, plus a crew of 10 for the week that crews overlap between missions. This common module includes a wardroom, galley, shower, waste management compartment, laundry, refrigerator and freezer, sleep accommodations and crew health care system accommodations. These items are either identical to or slightly modified from the Space Station Freedom designs. The allocated sleep volume, including storage, is the same as that provided aboard Skylab, proven adequate for an 84-day mission. The sleep restraints are in potential dual-use locations, and further study is required to determine the suitability of these locations. The crew health care system exercise facility is deployed on orbit in a radial port location.

Stowage volume for crew durable items and consumables is provided by the common habitation module, the Columbus Attached Pressurized Module, the Japanese Experiment Module, and a closet module, which is a modification of the mini-pressurized logistics module provided by the Italian Space Agency. The closet module is permanently attached to the common habitation module radial port and serves as a pantry for the Space Station as well as providing other required stowage volume. The total Space Station stowage includes a short duration (14 day) food supply in the common habitation module galley, with remaining food in the closet module. Consumables required for a 45-day skip cycle are provided.

The weight summaries of a common module are shown in Table 8. The weight for the laboratory module includes all on-orbit weight at Permanent Human Capability except payloads (International Standard Payload Racks). The weight for the habitation module includes all on-



(1) Hatch includes optical-quality window

ACM	Atmosphere control and monitoring	C&T	Communications and tracking
ACRV	Assured crew return vehicle	DMS/AV	Data management system/audio visual
APM	Attached pressurized module	MPLM	Mini-Pressurized Logistics Module
ARS	Atmosphere revitalization system	ISPR	International standard payload rack
CCWS	Command and control workstation	TCS	Thermal control system
CHeCS	Crew health-care system	WMC	Waste management compartment

Figure 16
Common habitation module

Table 8
Weight summaries for common core-laboratory and common habitation modules (pounds).

Subsystem	Laboratory*	Habitation
Structures	14,216	14,074
Mechanisms	3,508	3,138
Data Management	2,453	2,275
Environmental Control and Life Support System	3,598	4,295
Electrical Power	1,739	1,402
External Thermal Control	286	226
Extravehicular Activity	63	63
Internal Audio/Video	506	4€7
Internal Thermal Control	2,347	2,164
Crew Systems	1,161	928
Vacuum Vent	1,081	0
Total	30,958 lbs	29,032 lbs

* Excluding International Standard Payload Racks

orbit weight at Permanent Human Capability. The habitation module weight represents the launch configuration of a partially outfitted module. Habitation module outfitting is completed on a subsequent flight.

Mission Considerations

Orbital Inclination

Three potential orbital inclinations were considered for the Space Station: 28.8 degrees, 43 degrees and 51.6 degrees. Inclinations above 33 degrees allow dual access to the Space Station from the United States and Russian launch sites, but the higher inclinations significantly penalize Space Shuttle performance. At lower inclinations, the Space Station can utilize the standard Space Shuttle external tank and can be assembled at the operational 220 nautical mile orbit. The pressurized module launches will require some off-loading or downsizing if advanced solid rocket motors are not available. At 43 degrees or higher, an aluminum lithium external tank is required for all flights, and the assembly is identical to that at 28.8 degrees. Placement at 51.6 degrees inclination requires an aluminum lithium external tank beginning with the first assembly flight, occasional assembly at lower orbits ranging from 170 to 200 nautical miles, and greater off-loading or downsizing of pressurized modules if the advanced solid rocket motor is not also available. Assembly manifests for 28.8 and 51.6 degree inclinations are addressed in the Assembly Scenario section. Launch windows are more constrained for the high inclinations. Assembly missions at the 28.8 degree inclination have launch windows of 52 minutes, whereas the launch windows at 51.6 degrees are five minutes.

An advantage in power generation is realized at high inclinations, since the length of time in sunlight increases with inclination. The 28.8 degree inclination orbit provides for viewing up to 48 percent of the Earth and an equal percentage of zenith celestial sphere viewing coverage. The 51.6 degree inclination orbit allows 78 percent viewing coverage of the Earth or celestial spheres. The micrometeoroid and radiation environments are more favorable at the 28.8 degree inclination, with the orbital debris environment being about 12 percent worse for a 51.6 degree inclination orbit.

Orbital Environments

An analysis shows that the probability of no penetration for the Option A Space Station designs range between 70 and 80 percent for 10 years, depending on the configuration and orientation. The probability of no penetration for any individual critical system is higher than that for the overall Space Station. Incorporation of Space Station Freedom debris protection enhancement approaches, currently under study, could improve the overall Option A Space Station protection to approximately 90 percent probability of no penetration. The habitation module and laboratory module would require approximately 2600 pounds in weight increase to meet this number.

The 28.8 degree and 51.6 degree orbital inclinations, with an altitude of 220 nautical miles, give maximum beta angles of 52.3 degrees and 75.1 degrees respectively. At 28.8 degrees, the time in sunlight per orbit varies from 61 to 68 percent. At 51.6 degrees, the time in sunlight varies from 61 to 100 percent. Continuous time in sunlight occurs three to four times per year and has a maximum duration of five days. As stated earlier, the 51.6 degree inclination orbit provides higher power generation to the station system than 28.8 degree inclination.

Flight Modes and Propellant Utilization

Flight Orientations: It was necessary early in this design to determine the Space Station orbital orientation (attitude) and flight mode, which provides the best combination of electrical power, thermal control, and attitude control capability (momentum management), while maintaining acceptable microgravity and viewing conditions. This challenge was increased by the need to use one type of rotation joint instead of two, to maintain design simplicity.

Potential flight modes that were considered include the solar inertial attitude, the "arrow/combination" mode, and the "torque equilibrium attitude/combination" mode. In the solar inertial attitude, the Space Station would be oriented so the solar arrays are always perpendicular to the Sun. This allows full illumination of the arrays when the Space Station is in sunlight. In the arrow/combination mode, the Space Station would be oriented with the Space Station truss structure aligned with the velocity vector (direction of flight), like an arrow. The Space

Station would perform periodic 90 degree rotations about the velocity vector to orient the solar arrays alternately in the orbit plane or perpendicular to the orbit plane to maximize illumination of the solar arrays. The torque equilibrium attitude/combination flight mode is a variation of the arrow mode and is the preferred mode. The Space Station flies with the inertia principal axis oriented along the direction of flight, with additional slight offset due to aerodynamic torques. This results in the truss (body axis) flying at an offset angle from the velocity vector with periodic 90 degree rotations as in the previously discussed mode. Table 9 indicates the offset angles of the body axis with respect to the local-vertical coordinate axis. The truss maintains a constant offset angle from the velocity vector. The near in-orbit plane columns in Table 9 indicate how close angles 2 and 3 are to the ideal value of zero degrees. The ideal values for the near perpendicular-to-orbit plane columns are 90 degrees. The configurations with orbiter attached typically have larger offset angles than those without the orbiter attached.

The torque equilibrium attitude/combination flight mode and a timeline for the Space Station reorientations is illustrated in Figure 17. This flight mode allows good celestial and Earth pointing. Favorable viewing conditions are provided 72 percent of the time when the Space Station is oriented with the solar arrays nearly perpendicular to the orbit plane. The microgravity environment allows relatively constant conditions except during the periodic Space Station reorientation maneuvers that occur at 8 to 56-day intervals.

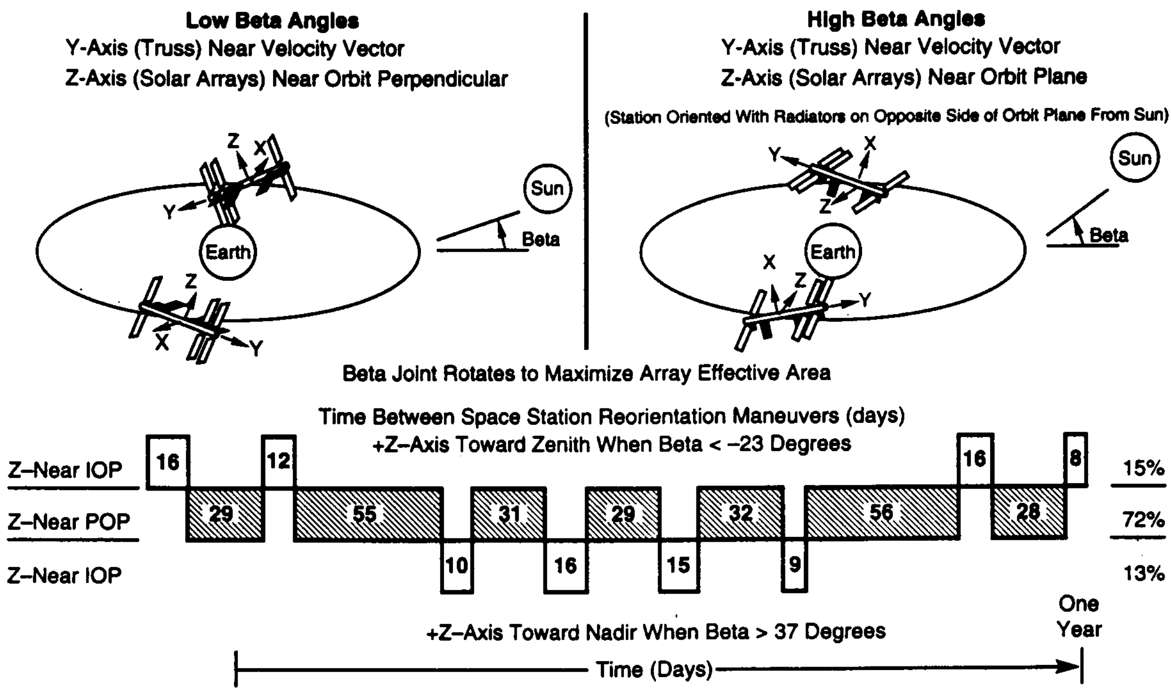
Reboost Requirements: For assembly at 28.8 degree inclination, the Space Station will be reboosted immediately after the end of each assembly mission to an altitude of 225 to 235 nautical miles. These reboost intervals and altitudes, using Option A-1 as an example, are shown in Figure 18. The reboost frequency in the Permanent Human Capability phase is assumed to be 90 days, which is the same interval used for Space Station Freedom. The reboost scenario during Space Station assembly at the 28.8 degree

Table 9
Space Station flight orientation offset angles

Definitions: 1. Angle Between Y-Axis (Truss) and Velocity Vector
2. Angle Between Z-Axis (Solar Arrays) and Orbit Plane
3. Angle Between X-Axis (PV Radiators) and Orbit Perpendicular

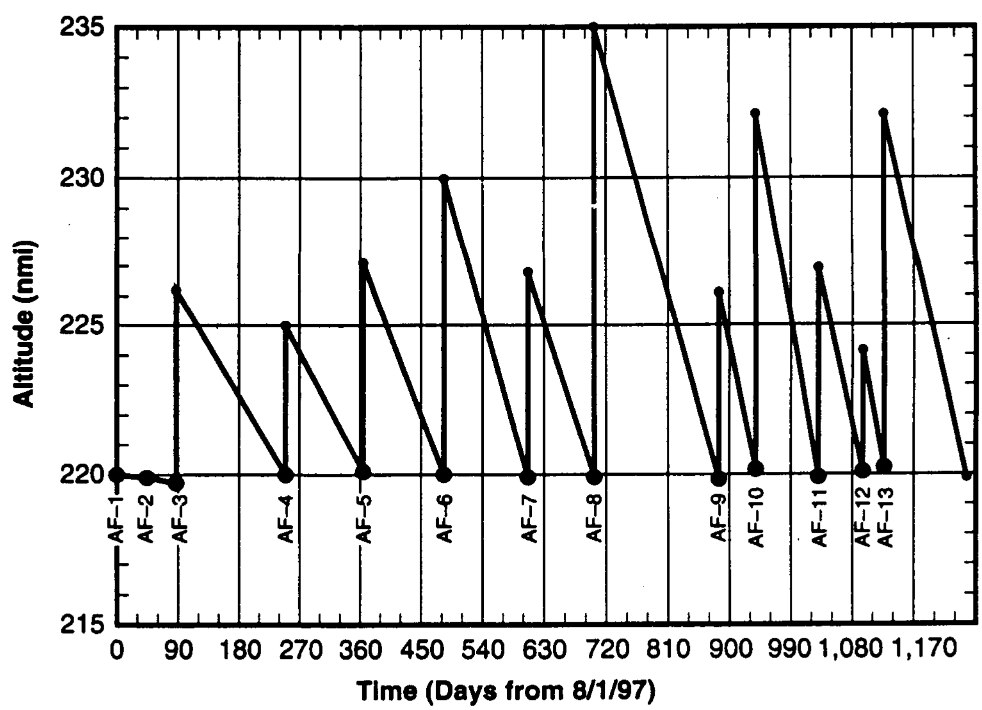
Flight Orientations	All	Near IOP		Near POP	
Offset Angle Number	1	2	3	2	3
Power Station With Orbiter	6.6	1.5	7.0	83.0	88.5
Power Station Without Orbiter	1.3	1.3	1.8	88.2	88.7
HTC With Orbiter (A–1)	7.4	11.6	13.8	76.2	78.4
HTC With Orbiter (A–2)	43.9	21.7	27.9	62.1	68.3
HTC Without Orbiter	5.4	0.3	0.7	89.3	89.7
IHTC With Orbiter (A–1)	24.0	44.2	49.8	40.2	45.8
IHTC With Orbiter (A–2)	14.3	16.5	16.8	73.2	73.5
IHTC Without Orbiter	2.7	0.6	0.6	89.4	89.4
PHC With Orbiter (A–1)	7.8	34.2	34.9	55.1	55.8
PHC With Orbiter (A–2)	10.4	22.1	22.7	67.9	67.9
PHC Without Orbiter	2.4	9.8	10.0	80.0	80.2

HTC Human Tended Capability
IHTC International Human Tended Capability
IOP In-orbit plane
LVLH Local vertical/local horizontal
PHC Permanent Human Capability
POP Perpendicular-to-orbit plane
PV Photovoltaic



IOP In-orbit plane
POP Perpendicular-to-orbit plane

Figure 17
Space Station flight orientations



AF Assembly flight
nmi Nautical miles

Figure 18
Altitude time history

Table 10
Propellant utilization budget

Option A–1 Propellant Budget

Function	Power Station	Human Tended Capability	International Human Tended Capability	Permanent Human Capability (PHC) (Yearly Req.)
Momentum Management	144 lb	607 lb	8,848 lb	2,341 lb
Reboost	220 lb	680 lb	3,835 lb	5,085 lb
Attitude Control	71 lb	121 lb	503 lb	364 lb
Total Per Phase (Number of Days)	435 lb (248)	1,408 lb (172)	13,186 lb (506)	7,790 lb (365)

- Bus–1 contains 11,660 lb of bi-propellant
- Attitude Control System average I_{sp} = 280 sec
- Reboost average I_{sp} = 300 sec
- Flight Schedule as of 5/14/93
- Altitude 220 nautical miles, 2 σ atmosphere

Grand Total PHC + 1 year 22,819 lb

Option A–2 Propellant Budget

Function	Power Station	Human Tended Capability	International Human Tended Capability	Permanent Human Capability (PHC) (Yearly Req.)
Momentum Management	46 lb	246 lb	3,605 lb	953 lb
Reboost	425 lb	880 lb	4,900 lb	6,395 lb
Attitude Control	129 lb	109 lb	2,062 lb	880 lb
Total Per Phase (Number of Days)	600 lb (248)	1,235 lb (172)	10,567 lb (506)	8,228 lb (365)

- Space station propulsion module contains 6,600 lb of mono-propellant per module, average I_{sp} = 230 sec
- Flight schedule as of 5/14/93
- Altitude 220 nautical miles, 2 σ atmosphere

Grand Total PHC + 1 year 20,630 lb

orbit inclination requires approximately 40 percent less propellant than the 51.6 degree inclination during the assembly of the Space Station. This is because the performance of the Space Shuttle at 28.8 degrees allows all missions to reach 220 nautical miles, whereas at the 51.6 degree inclination some assembly flights may occur as low as 170 nautical miles.

The aerodynamic forces and moments acting on the Space Station in low-Earth orbit are strongly influenced by the solar arrays. Option A aerodynamic drag can be reduced from that used in Figure 18 by "feathering" or rotating the solar arrays so that they are edge-on to the velocity vector. This reduces the propellant requirement for reboost and could be used when maximum electrical power is not required by the Space Station payloads. Sufficient propellant is available at each stage of assembly to reboost the station to higher altitudes than those shown. Using a combination of such reboost and feathering of the arrays, orbital lifetimes of two to three years are possible at each stage.

Propellant Utilization Budget: The complete propellant budget for reboost, attitude control and momentum management is summarized in Table 10. This table lists the propellant required to complete each phase of the Space Station assembly and provides an estimated yearly propellant requirement for the Permanent Human Capability phase. The propellant utilization budget was calculated using a two-sigma atmosphere model at the peak of the 11-year solar cycle, representing the most unfavorable expected atmosphere conditions. These propellant requirements should decrease as the solar cycle moves toward minimal activity.

Rendezvous Approach

The approach to rendezvous assumed for Option A is identical to the Space Station Freedom program approach. Prior to rendezvous, the Space Station will be reoriented to an attitude with the truss perpendicular to the orbit plane. For Option A-1, the solar arrays will be perpendicular to the orbiter approach corridor, and for Option A-2 they will be parallel to the orbiter approach corridor. The orbiter approach corridor to the Space Station is the same as planned for Space Station Freedom. The opening between the solar arrays has been reduced from about 266 feet in Space Station Freedom to about 118 feet in Option A-1 and 156 feet in Option A-2. A preliminary assessment of orbiter plume loads was conducted, and it indicated a potential negative margin for solar array boom loads. The Option A concept includes orbiter thruster modifications to minimize the plume loads; other solutions are also being investigated.

Assembly Scenario

Assembly Flight Manifests

The assembly phase of the Space Station consists of assembly flights (including outfitting flights), utilization flights and logistics flights. Some utilization flights include partial complements of logistics or other equipment, but each is mostly payload-related. The primary content and weight of each assembly flight is shown in Table 11. The primary difference in the assembly scenario for Options A-1 and A-2 can be seen in the first two flights. For Option A-1, the propulsion system (Bus-1) is launched on assembly flight 1, with the power elements on the second flight. Option A-2 launches equivalent hardware, but in reverse order. Flights 3 and subsequent flights are basically the same for both options except for control moment gyro launches. In Option A-1, control moment gyros are from the Bus-1 program and are launched with the Bus-1 on flight 1. In Option A-2, control moment gyros are from Space Station Freedom and launch on flight 3, with a backup control moment gyro on flight 5.

Launches of the international elements (flights 7 through 9) will require some off-loading of racks or redesign of the current modules to stay within the Space Shuttle capability. Launch of the common habitation module also requires off-loading of some racks. All quoted launch weights include an 1,800 pound Space Station margin. A Space Shuttle external airlock is included as part of the launch weight on flight 5 and subsequent flights. The 3,500 pound Space Shuttle manager's reserve is maintained on all flights. Weight contingencies include 5 to 10 percent on Space Station Freedom program elements and 20 percent on new elements.

After establishing the Power Station, utilization flights are initiated that take advantage of the existing on-orbit Space Station capability. In addition to carrying experiments, selected portions of these later flights carry limited Space Station outfitting racks and hardware. The Space Station Remote Manipulator System is launched on a utilization flight following assembly flight 4 for Option A-1, and on the second assembly flight in Option A-2. The Special Purpose Dexterous Manipulator is launched on assembly flight 5 for both options.

Option A assembly buildup scenarios have also been compiled for the 51.6 inclination orbit. Shown in Table 12 is a candidate assembly scenario for Option A-1 at the 51.6 degree inclination. This table is based on using the Space Shuttle aluminum lithium external tank for all assembly flights. As shown in Table 11, the delivery altitude is adjusted compared to the 28.8 degree inclination data. These lower assembly altitudes for the 51.6 degree option could be raised, but it would require additional off-loading or redesign of the launch elements (1,000 pounds off-loading per 10 nautical mile increase). This could result in remanifesting additional assembly flights. The advanced solid rocket motor is not available until early in the year 2001 and cannot be used to launch the heavy International Partners' laboratory modules and the habitation module. It is, however, an effective contribution to logistics.

Assembly Operations

For assembly flights prior to Human Tended Capability, the orbiter will be berthed via the unpressurized berthing mechanism to an adapter plate located on the Space Station truss. The

Table 11
Option A assembly scenario, 28.8 degree inclination, 220 nautical miles altitude

Assembly Flight	Components	Launch Weight, lb Option A–1	Option A–2
1	Propulsion, Bus–1 (A–1)	36,289	
	Truss and Power Equipment, Solar Array, Batteries (A–2)		39,600
2	Truss and Power Equipment, Solar Array, Batteries (A–1)*	32,078	
	SSRMS, SSF Propulsion Modules (A–2)		38,095
3	Truss, Thermal Control, and Avionics	33,847	36,047
	Power Station		
4	Common Core/Lab	37,284	37,284
	Human Tended Capability		
4a	MPLM, 11 Lab Racks, Payloads	37,800	37,800
5	Truss, Thermal Control (2nd Set), and SPDM	35,386	35,373
6	Truss, Power Equipment, and Solar Array (2nd Set)	32,855	37,104
7	Japanese Experiment Module	37,800	37,800
7a	MPLM, 10 JEM Racks, Cryo Tanks, Payloads	37,800	37,800
8	ESA Attached Pressurized Module (APM)	37,800	37,800
8a	MPLM, 11 APM Racks, Payloads	37,800	37,800
9	JEM EF, ELM PS, & ES	37,800	37,800
	International Human Tended Capability		
10	Truss, Power Equipment, and Solar Array (3rd Set)	29,695	31,563
11	Common Module/Hab	37,541	37,541
12	Airlock and Closet Module	37,164	37,164
13	2 Assured Crew Return Vehicles (Soyuz)	37,759	37,759
	Permanent Human Capability		

APM Attached Pressurized Module
ELMES Experiment Logistics Module Exposed Section
ELMPS Experiment Logistics Module Pressurized Section
ESA European Space Agency
JEMEF Japanese Experiment Module Exposed Facility
MPLM Mini-Pressurized Logistics Module
SPDM Special Purpose Dexterous Manipulator
SSF Space Station *Freedom*
SSRMS Space Station Remote Manipulator System

* SSRMS for Option A–1 launched on flight 4a

orbiter will be positioned in such a fashion to allow sufficient reach and free use of its remote manipulator system. The Space Station elements brought up in the cargo bay will be unloaded and positioned for attachment by the Space Shuttle Remote Manipulator System. Using currently designed hardware, crew extravehicular activity will be required to complete the final attachment and the release of various holddown mechanisms in preparation for deploying antennae, solar arrays, radiators, etc. At the end of each flight, the unpressurized berthing mechanism will be repositioned near the end of the new truss segment in preparation for the next flight. This is done by unlatching the unpressurized berthing mechanism from the truss, moving the truss with the Space Shuttle Remote Manipulator System and relatching the unpressurized berthing mechanism in its new location.

After Human Tended Capability is reached, the orbiter will dock at the laboratory to continue assembly. From this point on, the Space Station Remote Manipulator System and the Special Purpose Dexterous Manipulator will be available for use. A typical scenario consists of the following activities. The new Space Station element is removed from the cargo bay using the Space Shuttle Remote Manipulator System and handed off to the Space Station Remote Manipulator System. If the attachment location is within reach, the new element is installed at this time. If not, it will be temporarily stowed on the truss via the payload and orbital replacement unit accommodation mechanism. The Space Station

Table 12
Option A-1 assembly scenario, 51.6 degree inclination, variable altitude

Assembly Flight	Components	Launch Weight, lb	Shuttle Lift Capability, lb	Assembly Altitude, nmi
1	Propulsion, Bus–1	36,289	37,000	194
2	Truss, Power Equipment, Solar Array, Batteries	32,078	35,200	193
3	Truss, Thermal Control, Avionics	33,847	35,200	193
	Power Station			
4	Common Core/Lab	37,284	37,500	170
	Human Tended Capability			
4a	MPLM, 11 Lab Racks, SSRMS, Payloads	34,500	35,200	193
5	Truss, Thermal Control (2nd Set), and SPDM	35,386	35,500	190
6	Truss, Power Equipment, and Solar Array (2nd Set)	32,855	34,500	200
7	Japanese Experiment Module (JEM)	37,500	37,500	170
7a	MPLM, 8 Racks, Cryo Tanks	34,500	35,800	187
8	ESA Attached Pressurized Module (APM)	37,500	37,500	170
8a	MPLM, 11 Racks, Payloads	34,500	35,900	186
9	JEMEF, ELMPS/ES	37,500	37,500	170
	International Human Tended Capability			
10	Truss, Power Equipment, and Solar Array (3rd Set)	29,695	36,200	183
11	Common Module/Hab	37,541	37,500	170
12	Airlock and Closet Module	37,164	37,500	170
N/A	Soyuz Not Launched on Shuttle			
	Permanent Human Capability			

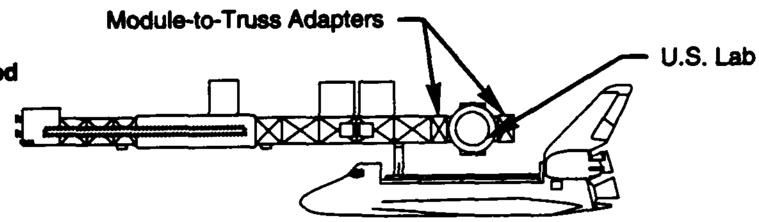
APM	Attached Pressurized Module	MPLM	Mini-Pressurized Logistics Module
ELMPS/ES	Experiment Logistics Module Pressurized Section/Exposed Section	nmi	Nautical miles
ESA	European Space Agency	SPDM	Special Purpose Dexterous Manipulator
JEMEF	Japanese Experiment Module Exposed Facility	SSRMS	Space Station Remote Manipulator System

Remote Manipulator System will then move to another location to gain proximity to the attachment point. The new element will then be detached from the payload and orbital replacement unit accommodation mechanism and positioned for attachment. This added operation is due to the deletion of the mobile transporter and adds to the assembly time. A typical operations scenario is shown in Figure 19.

Typical assembly flights will require a crew size of five, a mission duration of seven days and extravehicular activity times of up to 24 crew hours. The exception is flight 7, which will deploy the Japanese Experiment Module. It is estimated that this flight may require a mission duration of 12 days and extravehicular activity times of up to 32 crew hours.

At the end of each flight (except flight 1 of Option A-2), the Space Station will be left as a fully functional spacecraft with its own guidance, navigation and control, with the ability to change and maintain its orbit with the ability to maintain communication with the ground and with the ability to generate its own electrical power. If an interruption were to occur in the assembly flights, the Space Station would be able to safely remain in orbit for an extended period. The only exception to this is the first flight of the Option A-2. On this flight the first element is left in a completely passive mode and will decay from orbit in three to five years if not further assembled.

The primary differences from Space Station Freedom in the assembly of Option A will be fewer total flights, deletion of the mobile transporter and the interposition of the common core-laboratory between truss segments. As shown in Table 13, the lower number of flights leads to a significant reduction in total extravehicular activity (less than 230 hours versus Space Station Freedom's 381 hours). This option consists of fewer elements that require integration in orbit.



Requirements

- Rendezvous at 220 Nautical Miles
- Crew Size: 5
- Mission Duration: 7 days
- EVA Estimate:
  - 24 crew hours
- Flight Orientation:
  - Gravity Gradient (Orbiter's Tail to Earth, Belly Forward)
  - Orbiter Controls Attitude
- Integration Hardware:
  - 2 Remotely Operated Electrical Umbilicals (ROEU's)
  - Data Interface Unit
  - Grapple Fixture on Lab
  - Shuttle Remote Manipulator System

Major Operations

- Activate and Check Out Orbiter Interface (Data Interface Unit)
- Maneuver Station to Berthing Attitude
- Rendezvous and Berth to Power Station
- SRMS/EVA1: Attach Starboard Module-to-Truss Adapter Structure to Lab
- Connect ROEU's to Unpressurized Berthing Adapter
- Unberth Lab and Mate to S1 Truss
- EVA 1: Connect S1 Truss to Lab Utilities
- Check Out Lab System (Ground)
- SRMS/EVA 2: Attach Port Module-to-Truss Adapter Structure to Lab
- Unmate Unpressurized Berthing Adapter to S1 Umbilicals
- Deploy Space Station
- Bring Unpressurized Berthing Adapter Home
- Reboost Space Station

Figure 19
Option A-1 Space Station assembly flight 4 operations

The assembly of the Power Station is very similar in concept to early flights of Space Station Freedom. The major difference is that the unpressurized berthing adapter must be unlatched and relatched at a new location on the truss using the Space Shuttle Remote Manipulator System, instead of riding on the mobile transporter to a new location.

The physical attachment of the common core-laboratory to the truss, although different from Space Station Freedom, appears feasible. This operation will be done with the Space Shuttle Remote Manipulator System. The movement of this element from the cargo bay to its attachment location maintains adequate clearances and lies within the physical capabilities of the Space Shuttle Remote Manipulator System.

Systems Description

Bus-1 System (Option A-1)

The Bus-1 spacecraft (Figure 20) was developed by Lockheed Missiles and Space Company and provides an integrated system to position and control an attached payload. Bus-1 has successfully completed all three Space Shuttle safety reviews. The attitude and position reference system meets or exceeds current Space Station Freedom requirements. The reboost capability, as provided by the two main engines, is single-failure tolerant. The data management system is at least single-failure tolerant. Bus-1 has a health monitoring system with telemetry for

Table 13
Extravehicular activities required for assembly

A-1 Design			A-2 Design		
A-1 Redesign Assembly Flights	Number of EVA's Required	EVA Time (Crew Hours)	A-2 Redesign Assembly Flights	Number of EVA's Required	EVA Time (Crew Hours)
AF-1	0	0	AF-1	2	16
AF-2	2	24	AF-2	2	16
AF-3 (PS)	2	16	AF-3 (PS)	2	24
AF-4 (HTC)	2	24	AF-4 (HTC)	2	24
AF-4A	1	12	AF-4A	0	0
AF-5	1	12	AF-5	1	12
AF-6	2	24	AF-6	2	24
AF-7	2	24	AF-7	2	24
AF-7A	0	0	AF-7A	0	0
AF-8	1	6	AF-8	1	6
AF-8A	0	0	AF-8A	0	0
AF-9 (IHTC)	1	12	AF-9 (IHTC)	1	12
AF-10	2	24	AF-10	2	24
AF-11	2	24	AF-11	2	24
AF-12	2	16	AF-12	2	16
AF-13 (PHC)	1	6	AF-13 (PHC)	1	6

Summary	Total Mission Build Flights	Total Number of EVA's	Total EVA Crew Hours
A-1 Design	16	21	224
A-2 Design	16	22	228

EVA	Extravehicular Activity	PHC	Permanent Human Capability
HTC	Human Tended Capability	PMC	Permanently Manned Capability
IHTC	International Human Tended Capability	PS	Power Station
MTC	Man Tended Capability	SSF	Space Station *Freedom*

fault analysis and an autonomous response to on-orbit faults.

Bus-1 guidance, navigation and control is provided by an attitude reference system that senses deviations from a desired attitude and position. This information is processed within the data management system and acted on by a set of effectors. The attitude reference system contains nine rate gyros, three star sensors, two 3-axis magnetometers and nine Sun sensors. The effectors consist of six single-axis gimbaled control moment gyros, each rated at 1,700 foot-pound-seconds of angular momentum. In addition, 12 reaction control thrusters are used to assist the control moment gyros.

Bus-1 contains 11,660 pounds of nitrogen tetroxide and monomethylhydrazine propellants. The propulsion system is totally contained within Bus-1 and consists of four pressurization and six propellant tanks, feeding six pairs of 14-pound thrusters and two 200-pound reboost thrusters. The attitude control engines are positioned circumferentially around the aft end of Bus-1. This provides the Space Station with the capacity to rotate about its principal axes. The reboost thrusters provide translational capacity. To prevent an inadvertent thruster firing, the propulsion system has redundant failure tolerant valve sequencing and avionics hardware. There are provisions to change out Buses as required, without loss of attitude control. For Option A-1, investigation is continuing on a capability to resupply the Bus-1 propulsion system with

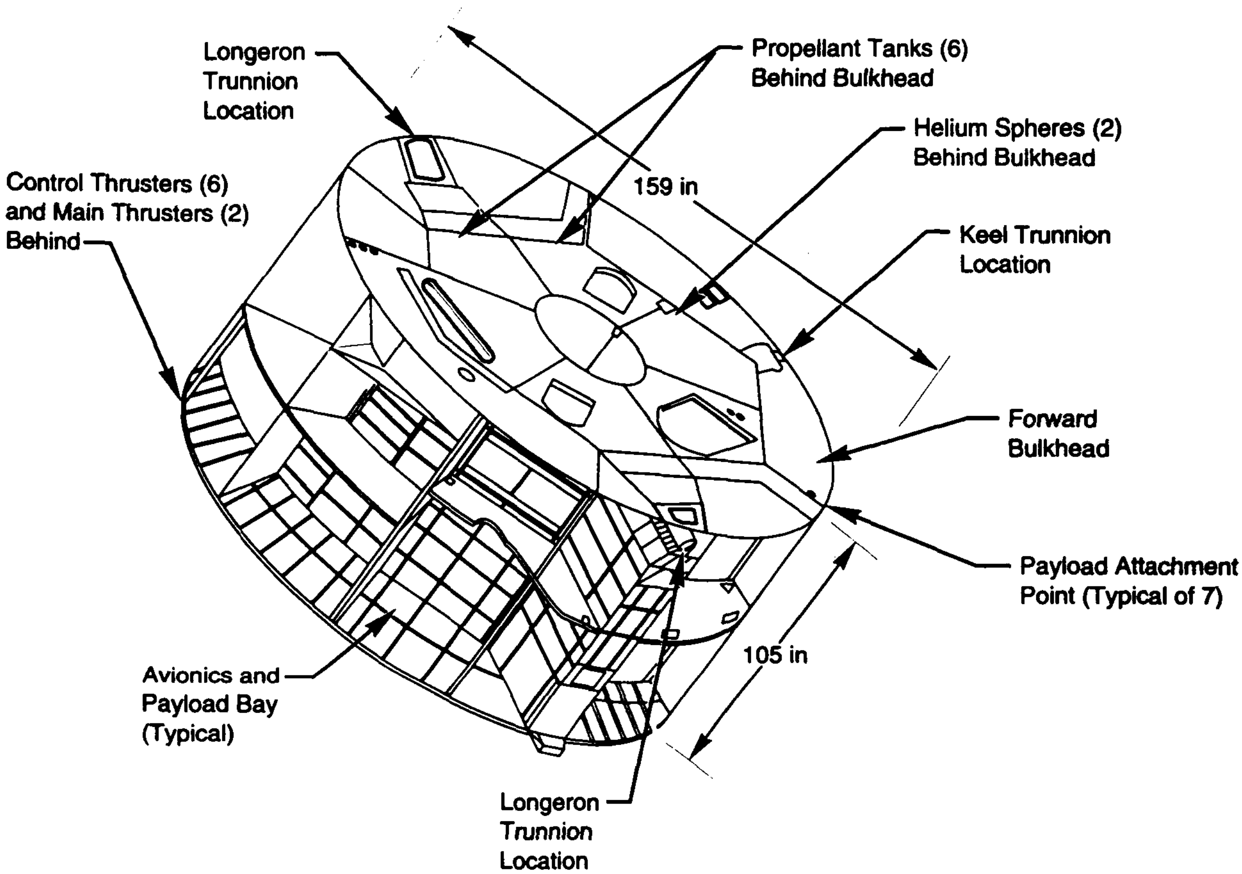


Figure 20
Bus-1 system (skin panels, avionics and deployables not shown)

propellant transferred from the orbiter's orbital maneuvering system tanks.

The power system supplies an average of 2.6 kW to 1.8 kW for Bus-1 active systems and 0.8 kW for the payload. For power generation, a fixed solar array of gallium arsenide-germanium cells, rated at 5 kW maximum output, is mounted to the payload structure; these cells could be mounted on the Bus-1/S4 interface structure for Space Station. For power storage, six 90 amp-hour nickel-hydrogen batteries are mounted inside Bus-1. Heat pipes are used for battery thermal control.

The data management system is composed of primary and secondary processors, both with A and B strings providing some internal redundancy, and hardwired attitude control logic for backup control. The command and control computer operates at 1.4 million instructions per second with 96 kilobytes of 24-bit word addressable memory. The system can store a maximum of 12,000 commands. A 100-channel serial input and output processor and a remote decoder multiplexer are also part of the data management system.

The communications system consists of a dual channel S-band transponder capable of 1 kbps on the uplink and 2 or 32 kbps for downlink, with four switchable antennas. The system is compatible with the spacecraft ground link system used by the United States Air Force. The S-band system could be made compatible with the NASA Tracking and Data Relay Satellite System, but would then be limited to 16 kbps downlink. Primary communications are effected by a three-axis antenna pointing system located on the aft bulkhead. The current primary Bus-1 communication electronics are not suitable for high rate Ku-band Tracking and Data Relay Satellite System communications.

The structure is built around a central hexagonal core that acts as the primary load-carrying backbone. The six fuel tanks are located within this hexagonal core. Bulkheads and transverse partitions are placed around this core, creating bays for equipment mounting. Three sill trunnions and one keel trunnion are located on the periphery for ground handling and to attach Bus-1 to the launch vehicle. While not specifically designed to meet the micrometeoroid and debris requirements, the structural configuration offers more inherent shielding than most other Space Station elements.

Bus-1 modifications for Option A-1 are: reaction control thruster repositioning and modification to ensure two-failure tolerant reboost capability; the addition of a mechanical adjustment to allow the orbit adjust thrusters to track the Space Station center of gravity; solar array relocation; the addition of an electrical converter, communication and data and mechanical interfaces, thermal closeout, and power and data grapple fixtures; software changes; and modification of the safe hold mode. An add-on communications system is being assessed for the potential to perform the communications and tracking function for the Space Station.

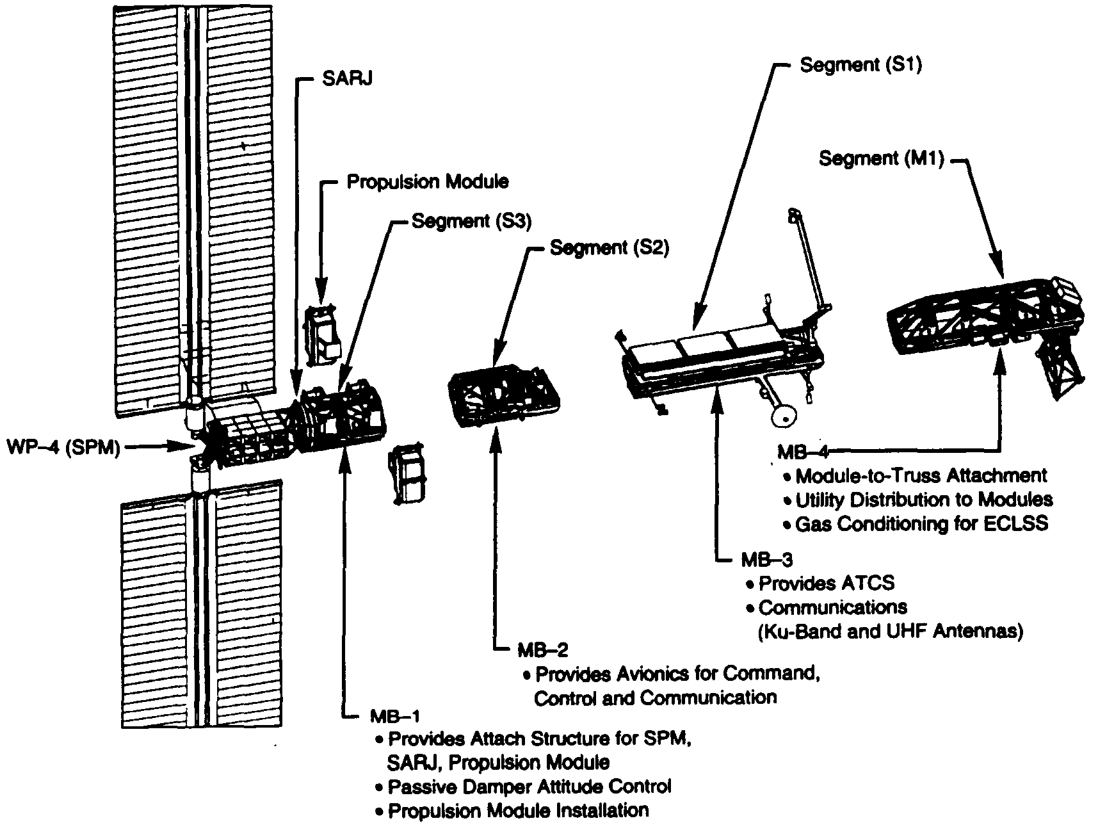
At this point, Bus-1 has good potential for replacing the Space Station Freedom propulsion and attitude control functions with a single piece of existing, self-sufficient, flight-proven equipment. However, more detailed analyses remain to be performed, such as full determination of the attitude control margins associated with Bus-1 control moment gyros. Also, since Bus-1 is not designed for on-orbit maintenance and repair, it must be replaced as a system. Based on its demonstrated reliability and inherent redundancy in design, Bus-1 changeout will be driven by propellant depletion rather than system failures. Data provided by the Lockheed Missiles and Space Company indicates that Bus-1 has operated for more than 40,000 hours on-orbit without a mission-ending failure, as evaluated using Space Station mission success criteria.

Structures and Mechanisms

Option A utilizes the existing Space Station Freedom structural design, materials ordered and tooling to the maximum extent possible. The types of mechanisms for Option A are the same as used on Space Station Freedom, with a reduced quantity. Several segments of the preintegrated truss have been eliminated for the A-1 configuration. The Space Station Freedom components located in truss segments designated as S3, S2, M1, P2 and P3 (Figure 21) are relocated to other remaining truss segments, or their functions are provided by the Bus-1 spacecraft. The remaining truss segments require modifications in order to accommodate such functions as utility distribution, orbiter berthing and avionics. Several other elements from Space Station Freedom are also eliminated; these include the solar alpha rotary joint assembly, the mobile transporter and the pressurized logistics module.

For Option A-1, a new truss segment between the Bus-1 and the integrated electronics assembly truss segment S4 is required. It is approximately 24 feet long to provide the spacing necessary for the Bus-1 reaction control system to clear the solar array panels. An unpressurized berthing adapter interface is provided on the truss segment to accommodate orbiter berthing. The Option A-1 configuration incorporates the existing design for the segment-to-segment attach system at the Bus-1 interface. The truss-to-integrated electronics assembly interface uses a four-point extravehicular activity attachment system similar to a design used on Space Station Freedom. Another new structure, similar to the interface between S4 and S3 on Space Station Freedom, is required to adapt the integrated electronics assembly truss segment to the S1 truss segment. Each end of the S1 truss segment uses the segment-to-segment attach system mechanism. The S1 truss segment will require modification to accommodate subsystems from the deleted truss segments. This includes two radiator panels, repackaging of existing systems and the addition of an unpressurized berthing adapter interface. Similar modifications and new structures are required for the port truss.

The Space Station Freedom laboratory module and the node are combined into a single element. Two-thirds of the laboratory module is merged with the radial port section of the node to form the common core-laboratory module. The six node berthing ports (common berthing mechanisms) are retained in the common core-laboratory, with no changes to the common berthing mechanism. Modifications to the existing node and laboratory component designs include: addition of six inches to the radial port section of the node, relocation of trunnions, addition of a structure to attach the module to the S1 and P1 truss segments, modification of a secondary structure to accommodate repackaging, and replacing the node end cone with the laboratory end cone. The module-to-truss adapter structure is attached to



ATCS	Active Thermal Control Subsystem	SARJ	Solar Alpha Rotary Joint
ECLSS	Environmental Control and Life Support System	SPM	Solar Power Module
MB	Mission Build	WP	Work Package

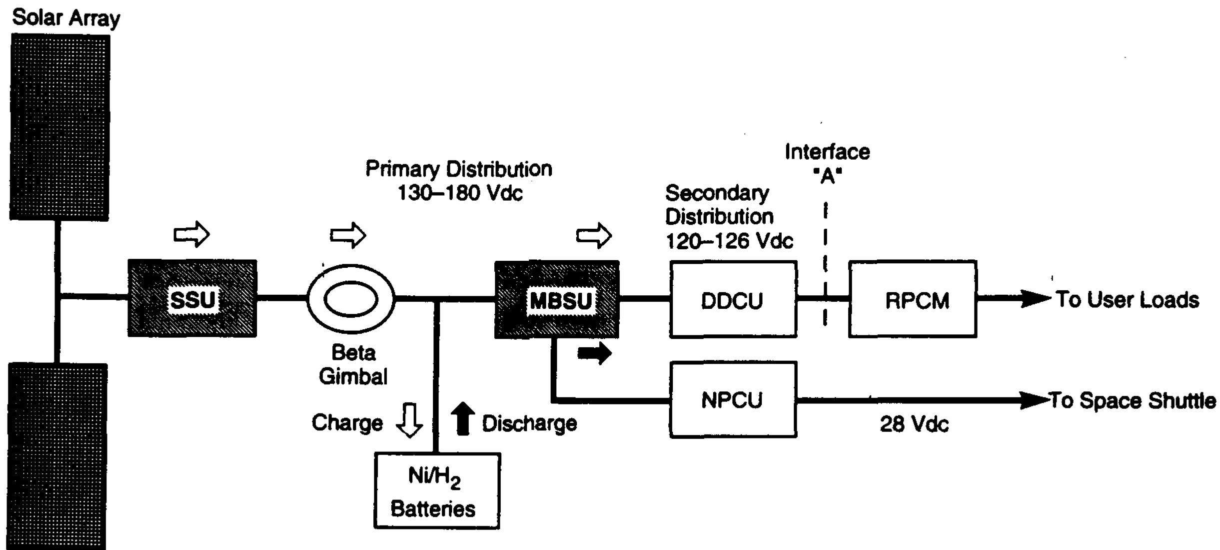
Figure 21
Space Station Freedom integrated truss assembly

the module by extravehicular activity, and the module is then connected to the S1 truss segment with the segment-to-segment attach system mechanism. The P1 truss segment will attach to the common core-laboratory in a similar manner. The module-to-truss adapters are stored on the S1 truss segment prior to assembly. The common core-laboratory requires additional analyses to assess the implications of the load path changes. The common core-laboratory structural design is also used for the habitation module, with no additional core resources provided at the berthing ports. An eight-inch-diameter Spacelab optical-quality window will be provided in one of the habitation hatches.

For the A-2 configuration, truss segments S2, M1 and P2 are deleted and the required functions of those segments are moved to the remaining truss segments. The deletion of the solar alpha rotary joint requires an adapter structure between the integrated electronics assembly and the S3 truss segment. A design similar to that used for Space Station Freedom has been selected. The A-2 configuration uses the common core-laboratory, common habitation module, and the module-to-truss adapter structure.

Electrical Power System

The electrical power system for Option A maintains the basic silicon solar array and nickel hydrogen battery concept used on Space Station Freedom. The exception to that design was the elimination of the alpha joint and the modification of the electrical power system's primary distribution architecture. The modular buildup approach of electrical power generation is maintained through the utilization of the Space Station Freedom Work Package 4 photovoltaic module. Each module provides a nominal 20 kW electric power generation increment. Option A's electrical power system architecture is shown in Figure 22.



SSU	Sequential Shunt Unit
MBSU	Main Bus Switching Unit
DDCU	DC-to-DC Converter Unit
NPCU	NSTS Power Converter Unit
RPCM	Remote Power Controller Module
Ni/H_2	Nickel Hydrogen
Vdc	Volts direct current

Notes:

Orbital Data	Max.	Min.
⇨ Sunlit	64	57
➡ Eclipse	36	29

▒ Redesigned or new in modified power distribution system

- Beta gimbal used for orbit tracking
- Shaded blocks indicate modified hardware

Figure 22
Electrical power system, modified distribution system

The beta joints on the photovoltaic module are used for solar tracking. Compensation for seasonal solar angle (beta angle) losses are minimized by an orientation maneuver at the optimum beta angle. The solar arrays are oriented perpendicular to the orbit plane for beta angles between minus 23 and plus 37 degrees and are flown in the orbit plane for other beta angles. The yearly orbit average power reduction of approximately seven to eight percent by the alpha joint deletion is justified by the reduced parasitic losses, mass, cost, operational complexity and improved reliability. The mode with arrays in the orbit plane is required only 28 percent of the year and allows periods of up to 56 days to occur between required maneuvers.

These changes from Space Station Freedom result in overall electrical power system efficiency improvements and enable a two-failure tolerant system at earlier Space Station buildup phases. The architecture changes reduce the mass and the thermal rejection requirements 2.7 kW (thermal) per photovoltaic module.

Power available at each Space Station buildup phase is shown in Table 14. Values shown are for both orbital average and yearly orbit averages. The power available includes effects of orientation and array-to-array shadowing. Performance on a specific day may vary due to attitude and/or time of year (see Figure 23). Option A-1 and A-2 numbers differ only slightly at certain phases of buildup due to torque equilibrium attitude and/or equipment differences.

At International Human Tended Capability, 27.4 or 26.0 kW of electricity (orbital average for A1 or A2) can be provided to the user when the orbiter is not present. Also, 31.0 or 30.0 kW (orbital average for A1 or A2) is available to the user at Permanent Human Capability with the addition of the third photovoltaic module. The interface to the international user is maintained as defined for Space Station Freedom. Power is

Table 14
Electrical power system configuration A-1 / A-2

Non-Torque Equilibrium Mode/Inclination = 28.8 Degrees, Power Budget (kWe)
(All calculations include solar array shadowing)

Flight Phase	Power Station	Human Tended Capability		International Human Tended Capability		Permanent Human Capability
	With Orbiter	Without Orbiter	With Orbiter	Without Orbiter	With Orbiter	Without Orbiter
Representative * Orbital Average (kW)	23.1/23.1	23.1/23.1	23.1/23.1	46.1/46.1	46.1/46.1	57.0/57.0
Yearly Orbital Average ** Power @ Interface "A" (kW yr/yr)	24.4/24.4	24.4/24.4	24.4/24.4	47.0/47.0	47.0/47.0	58.0/58.0
Housekeeping						
• U.S. Basic Sybsystems [1,2]	15.0/14.8	6.7/6.9	16.1/16.5	8.3/9.7	17.7/19.3	13.4/14.8
• Other Elements [3]	–	–	–	–	–	2.2/2.2
• Internationals [4]	–	–	–	10.4/10.4	10.4/10.4	10.4/10.4
Available for User (Orbital Ave.)	8.1/8.3	16.4/16.2	7.0/6.6	27.4/26.0	18.0/16.4	31.0/30.0
(Yearly Ave.)	9.4/9.6	17.7/17.5	8.2/7.9	28.3/26.9	18.9/17.3	32.0/31.0
Spacelab Users (max)	3.4/3.4					

Notes:

1 Includes Subsystems, Orbiter and Spacelab
2 Orbiter With 4 Cryo Tank Sets, 8 kW, 20-day stay
3 Includes ACRV, Cupola, Closet Module, and Airlock
4 CSA (1.43 kW), ESA (3.74 kW), NASDA (5.22 kW)
* LeRC calculated value for average eclipse day at beta angle of 27° and vehicle flying in Z/POP orientation.
** Derived from Lewis Research Center (LeRC) supplied data.

provided to Bus-1 after flight 3 and to the orbiter as required through the Power Station, Human Tended Capability, and International Human Tended Capability buildup phases. Space Station power is not required by the orbiter at Permanent Human Capability. Spacelab power requirements are also provided to the orbiter during the Power Station mission phase.

Thermal Control System

The Option A thermal control system collects, transports and rejects waste heat and maintains structures, systems and subsystems within their required temperature limits using active and passive approaches. The active system (Figure 24) consists of a photovoltaic system mounted on each photovoltaic truss segment, an external central system mounted on the central truss segments and a module internal thermal control system. The photovoltaic and the central external systems utilize the Space Station Freedom photovoltaic thermal control design: a single-phase ammonia system utilizing dual passage radiators, pumps and controls to provide a redundant system. The central system consists of a moderate- and a low-temperature fluid loop that is cross-strapped to the initial photovoltaic loop to provide two-failure tolerance to critical loads during buildup. This is a change to the central system on Space Station Freedom which is a two phase ammonia system. The common core-laboratory module's internal thermal control sys-

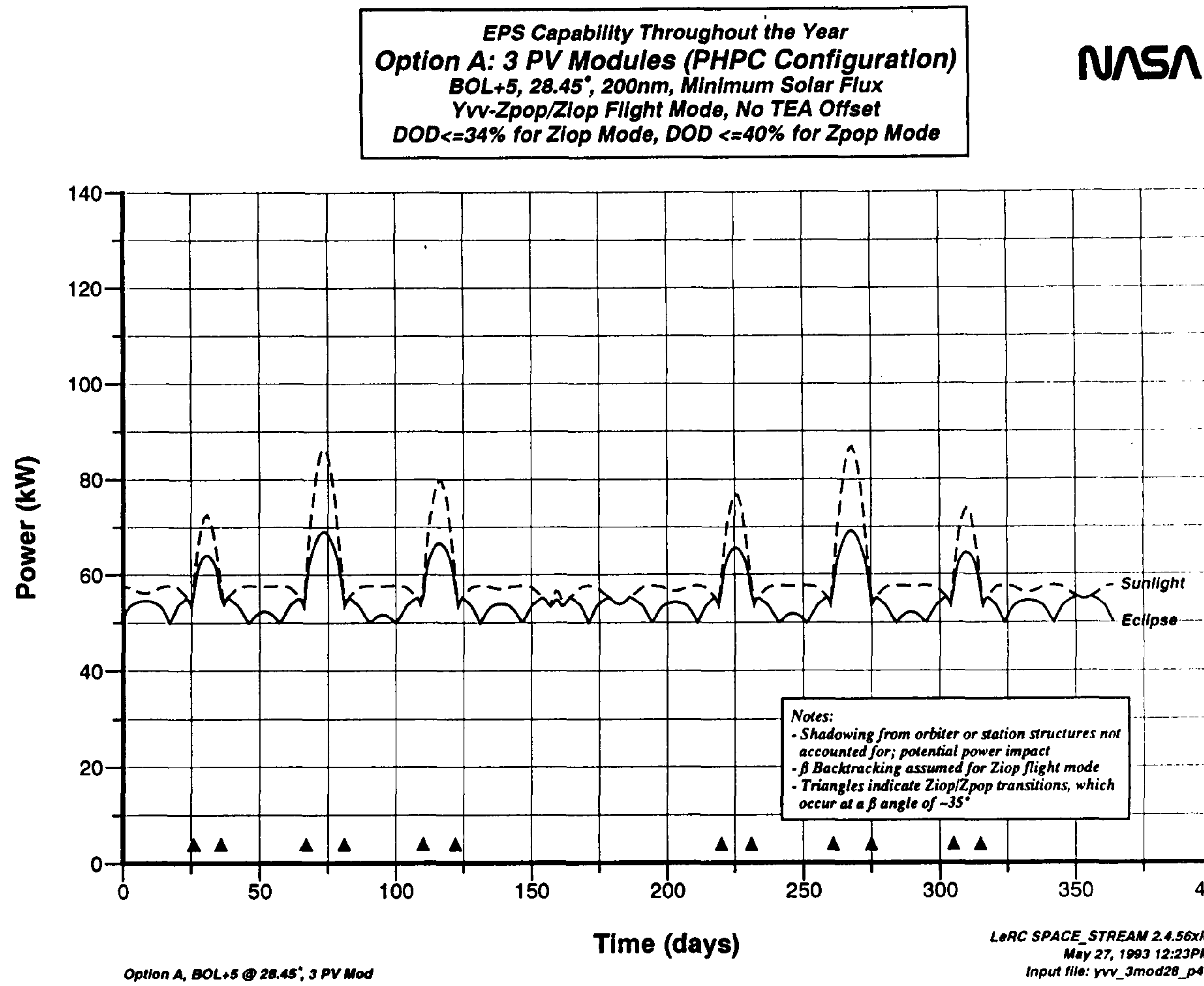
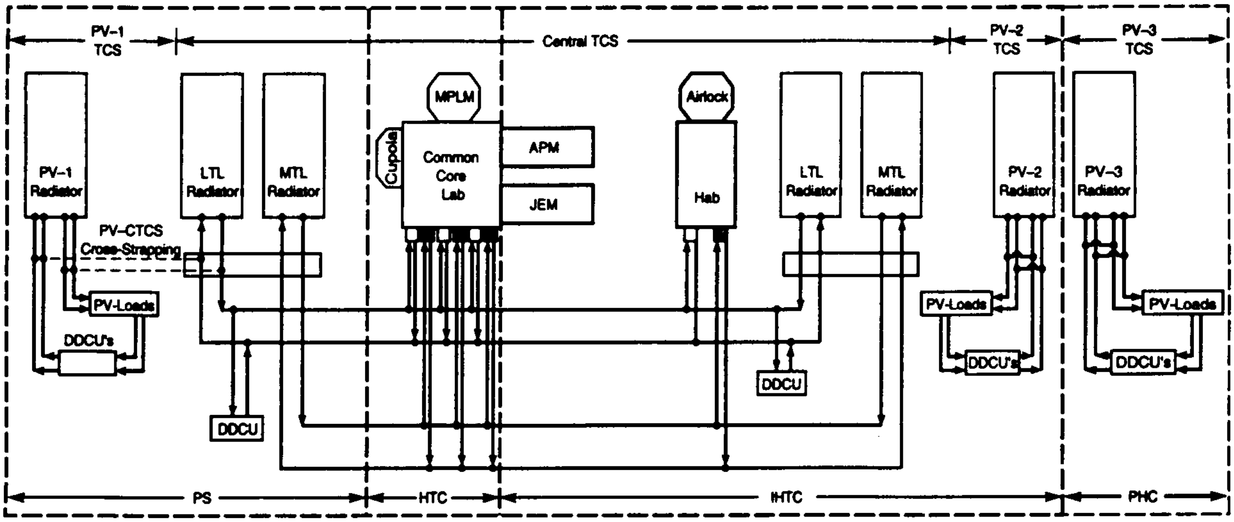


Figure 23
Option A: Three photovoltaic modules (Permanent Human Presence Capability configuration)

tem (Figure 25) utilizes water as the transport medium in two loops which are connected to the central system via heat exchangers on the module end cones. The moderate- and low-temperature loops are cross-strapped to provide redundancy for critical systems. This system also collects waste heat from the mini-pressurized logistics module and provides structural heating of the cupola. The laboratory also supports the Columbus Attached Pressurized Module and the Japanese Experiment Module via coolant connections to two additional sets of heat exchangers mounted externally on the laboratory. The common habitation module has a similar system and provides coolant support for the airlock. These internal systems are identical to the Space Station Freedom internal thermal control system.

The modules' passive thermal control system and truss-mounted equipment utilize heaters, insulation, coatings and isolators to maintain temperatures within required limits. Some truss-mounted equipment also uses passive radiators, louvers and phase change materials. Command and data management for both internal and external thermal control is provided by the onboard data management system.

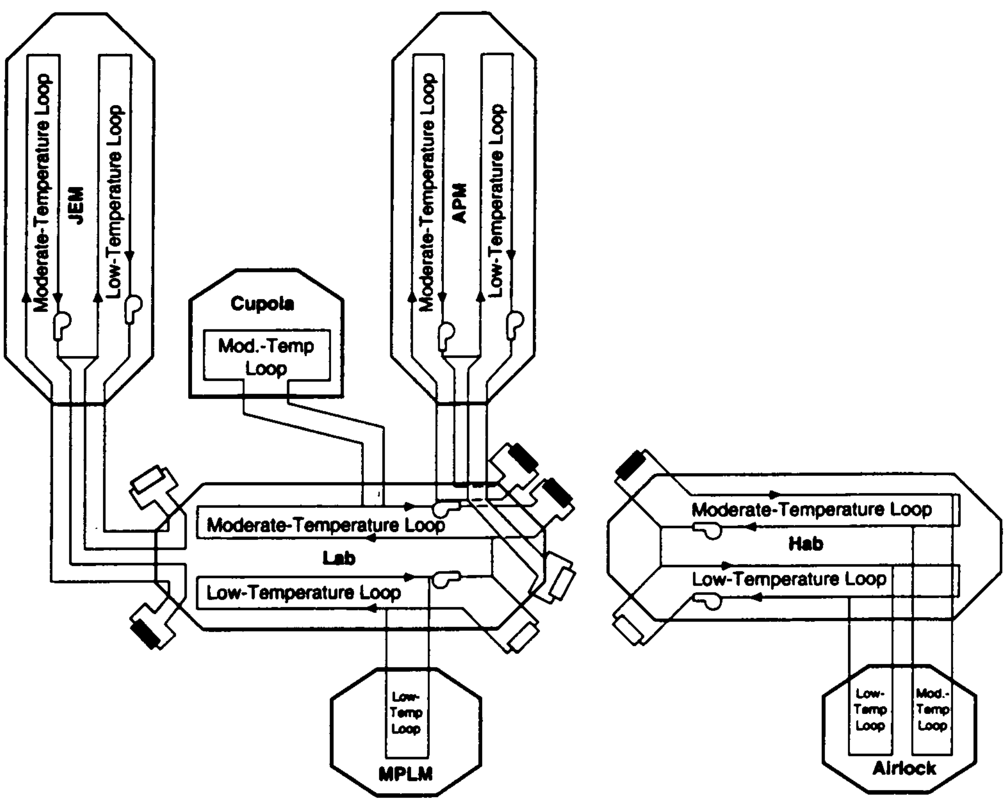
Table 15 summarizes the system characteristics and capabilities. Failure tolerance is improved over the baseline Space Station



APM	Attached Pressurized Module	MTL	Moderate-Temperature Loop
CTCS	Central Thermal Control System	MPLM	Mini-Pressurized Logistics Module
DDCU	DC-to-DC Conversion Unit	PV	Photovoltaic
LTL	Low-Temperature loop	TCS	Thermal Control System
JEM	Japanese Experiment Module		

□ LTL Heat Exchanger
▨ MTL Heat Exchanger

Figure 24
External active thermal control system overview



JEM	Japanese Experiment Module
APM	Attached Pressurized Module
MPLM	Mini-Pressurized Logistics Module

■ MTL HX
□ LTL HX

Figure 25
Internal thermal control system overview schematic

Table 15
Space Station thermal control system characteristics

Photovoltaic Thermal Control System (PVTCS)

- Utilizes WP04 baseline single-phase ammonia
- PV–1: 2 independent loops—single-failure tolerant to 50% pwr.
- PV–2,3: 2 cross-strapped loops—single-failure tolerant to 50% heat rejection
- PV TCS jumped to CTCS for two failure tolerance for station survival
- Deleted 6 BCDU's and 2 DCSU's
  - Added 2 MBSU's
- 2.7 kW (36%) load reduction from baseline (7.4 kW)
- PFCS performance:
  - Pump cap: 2,570 lb/hr @ 23.1 PSID and 1 °F
  - Power: 265 W average Weight: 210 lb
- Radiator perf.: Eight 2-sided panels 960 ft^2 rejects ~7.4 kW @ ~ 0 °F

	PS/HT	PHC
Weight (lb)	2,743	5,486
Power (W)	538	807

Central Thermal Control System (CTCS

- 6 WP02 two-phase ammonia radiators replaced by four WP04 single-phase radiators
- Two external temperature loops
- Central bus supports truss-mounted DDCU's and 14 kW and 25 kW heat exchangers mounted to lab end cone. APM and JEM heat exchangere also mounted to lab end cones.
- CTCS radiator performance estimates
  - LTL: 14 kW @ ~ 58 °F
  - MTL: 20 kW @ ~ 36 °F
- One WP04 PFCS for each radiator

	PS/HTC	PHC
Weight (lb)	9,812	19,624
Power (W)	538	1,060

Internal Thermal Control System (ITCS)

- WP01 baseline—single-phase water
- U.S. Lab: MTL–25 kilowatts HX
  LTL–14 kilowatts HX

Supports:
- Cupola window frame thermal control—
  Two refrigerator/freezers racks in MPLM with 1.8 kW/500 lb/hr
- APM and JEM with 1 MTL and 1 LTL HX ea.—
  HX's mounted to lab end cone
- MTL (61–65 °F): 2.5 kW housekeeping @ 636 lb/hr
  22.5 kW P/L @ 2,364 lb/hr
- LTL (38–42 °F): 4.1 kW housekeeping @ 2,084 lb/hr
  8.1 kW P/L @ 416 lb/hr

	HT	PHC
Weight (lb)	1,791	3,582
Power (W)	600	1,100

Passive Thermal Control System (PTCS)		Orbiter Thermal Control System
Truss-Mounted Equipment	Lab	
• Detailed truss layouts and passive thermal design to be accomplished in implementation phase.	• MLI wt: 1,240 lb Cold environment heat leak: 350 W Hot environ heat gain: 20 W • No design issues.	• Analyses indicate orbiter TCS performance is adequate.

APM	Attached Pressurized Module
BCDU	Battery Charge/Discharge Unit
CTCS	Central Thermal Control System
DCSU	Direct Current Switching Unit
HX	Heat Exchanger
JEM	Japanese Experiment Module
kW	Kilowatt
LTL	Low Temperature Loop
MBSU	Main Bus Switching Unit
MPLM	Mini Pressurized Logistics Module
MTL	Moderate Temperature Loop
PFCS	Pump and Flow Control Subassembly
PHC	Permanent Human Capability
P/L	Payload
PS/HT	Power Station/Human Tended
TCS	Thermal Control System
WP	Work Package
°F	Degrees Fahrenheit

Freedom design by modifying the central system to a design similar to the photovoltaic thermal control system and cross-strapping the two radiator systems. This also eliminates the development and verification of a second thermal control system. All of the system interfaces remain unchanged.

Propulsion System

The Bus-1 propulsion system, used in Option A-1, is described in the Bus-1 systems description section. Although not yet mature, several concepts are being investigated to resupply the Bus-1 propellant system with propellant transferred from the orbiter orbital maneuvering system tanks. The propulsion module for Option A-2 is identical to the Space Station Freedom propulsion system. There are two replaceable propulsion modules at the Power Station and Human Tended Capability phases, and four propulsion modules at the International Human Tended Capability and Permanent Human Capability phases. Each propulsion module weighs 11,300 pounds, including 6,800 pounds of hydrazine. There are ten 25-pound attitude control thrusters and three 55-pound reboost thrusters on each module. These thrusters are configured to allow the Space Station to translate and orient in all directions and attitudes (6 degrees of freedom). The propulsion module has three levels of inhibits, redundant failure tolerant valve sequencing and avionics hardware to prevent inadvertent thruster firing. When the propellant in the propulsion module is depleted, the entire module is replaced and returned from orbit for propellant resupply and reuse.

Guidance, Navigation and Control System

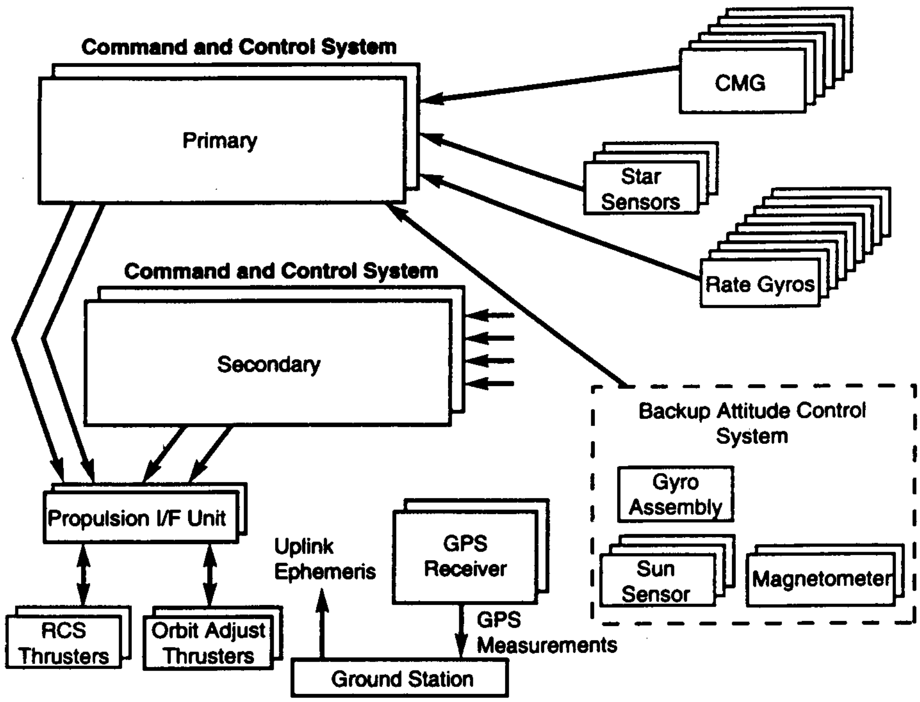
Hardware Functional Description: Although the actual hardware used varies from Option A-1 to Option A-2, the types of hardware required and their functions remain constant. Block diagrams of the Option A-1 and A-2 guidance, navigation and control systems are shown in Figures 26 and 27, with Option A-2 being identical to Space Station Freedom.

Space Station attitudes and attitude rates are measured by two different assemblies. The inertial sensor assembly consists of gyros that measure the three-axis inertial rates for stabilization purposes and as a backup to the star sensor inertial attitude reference. Inertial attitudes are determined by either star scanners (A-1) or star trackers (A-2). Either type measures the position and magnitude of stars, which can be compared to a catalog of known stars to determine inertial attitude.

The control system effects Space Station attitude changes through either the attitude control system thrusters or the control moment gyros. The control moment gyros provide the primary attitude control because they do not in themselves use propellant and because fine control (in low microgravity) can be achieved. The control moment gyros' capability will be exceeded (and reach maximum momentum storage capability) for some configuration and orientation combinations, and must be desaturated. The thrusters are used to desaturate the control moment gyros and also for certain large-angle attitude changes (reorientation to a completely new attitude). In addition, on Option A-2 only, the thrusters (or passive magnetic dampers) are used for primary attitude control during the early buildup phases when the control moment gyros are not operational.

Navigation is handled differently for the two options. Option A-1 uses a Global Positioning System receiver. Position information is received from Global Positioning System satellites already on orbit and relayed to the ground, where the position is calculated and sent back to the Space Station. Option A-2 uses radar systems on the ground to track and locate the Space Station. The position is then relayed to the Space Station.

Interfaces: The guidance, navigation and control standard interface consists of the state vector (position and velocity, attitude, and attitude rates), an indicator of the state vector quality, a vector that points to the Sun, solar eclipse times, and times when radio communication to the ground is made or lost. The users of this standard interface include the thermal control system, communications and tracking, the Japanese Experiment Module, payloads, the electrical power system and the orbiter. In addition to these standard interfaces, special interfaces are maintained with the data management system, ground control, the Japanese Experiment Module Remote Manipulator System and the propulsion system.



- Active guidance, navigation, and control after first flight, requires no passive dampers
- Six single-gimbal CMG's
  - 1,700 ft-lb-sec momentum storage each
  - High-torque capability
  - 353 lb each
- Twelve 14 lbf RCS thrusters
- Two 250 lbf reboost thrusters

CMG	Control Momentum Gyroscope
GPS	Global Position System
I/F	Interface
RCS	Reaction Control System

Figure 26
Option A-1 (with Bus-1) guidance, navigation and control subsystem

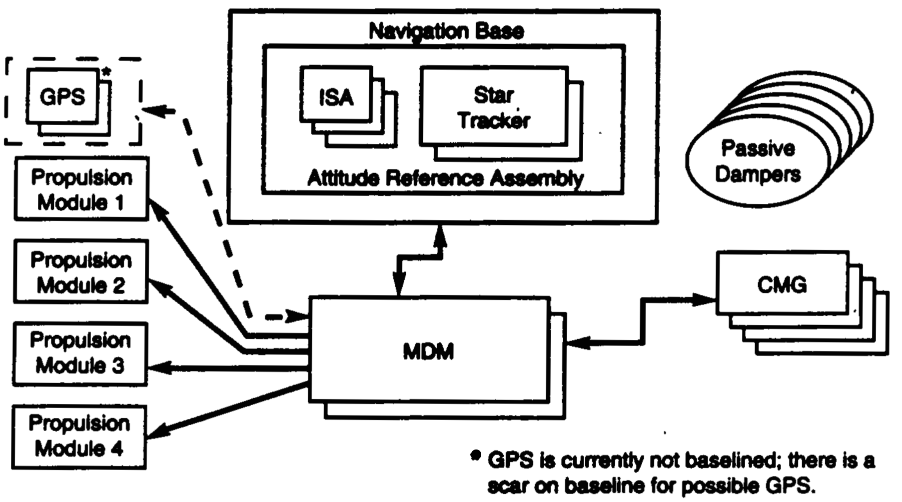
Data Management System

The data management system provides distributed data communications and processing for the Space Station. A schematic of this system appears in Figure 28.

The data system is based on a single processor design using the Space Station Freedom baseline multiplexer and demultiplexer, with some enhancements, as a replacement for all standard data processor based units. Option A's architecture also deletes the fiber optic networks and associated hardware components, and uses 1553B data buses for all system communications. Other data system hardware changes include replacement of the workstations with portable laptop computers and the use of a modified component of the orbiter display system to implement an interface with the orbiter.

A simplified software architecture is provided by deleting the object management protocol and many of the data management system standard services in Space Station Freedom. This significantly reduces software complexity and simplifies the software interface with the International Partners and with existing ground systems. Deletion of the standard services reduces schedule and program risks for software generation and integration.

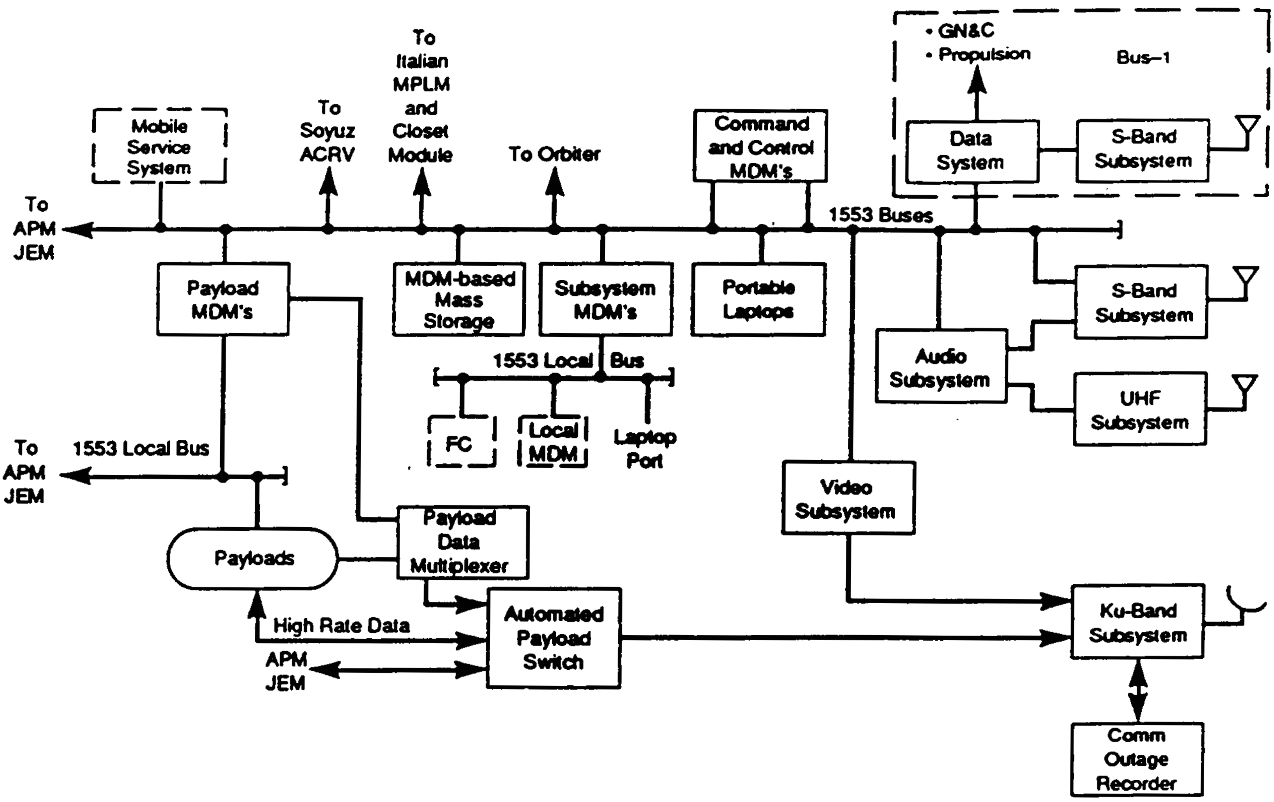
Verification is simplified due to the data bus architecture, separation of external truss and internal module functions, and distribution of subsystem control. The software development, verification, validation and build responsibility resides with the system hardware developer. A large centralized software test and verification facility is not required.



• Guidance, navigation, and control elements same as Space Station *Freedom*

GMG	Control Momentum Gyroscope	ISA	Inertial Sensor Assembly
GPS	Global Position System	MDM	Multiplexer Demultiplexer

Figure 27
Option A-2 guidance, navigation and control subsystem



ACRV	Assured crew return vehicle	JEM	Japanese Experiment Module
APM	Attached Pressurized Module	MDM	Multiplexer/demultiplexer
FC	Firmware controller	MPLM	Mini-Pressurized Logistics Module
GN&C	Guidance, navigation, and control		

Figure 28
Communications and data management system

The 802.4 data bus and fiber optic network interfaces with the International Partners are deleted. The 1553B data buses now provide an interface between modules for core and payload data. An enhanced capability for routing and multiplexing payload data is provided by automated payload switches and payload data multiplexers. This provides payload-to-payload data transfers and efficient use of the Ku-band downlink. The Space Station Remote Manipulator System and the Special Purpose Dexterous Manipulator require a dedicated robotics workstation separate from the Space Station data system.

Communications and Tracking System

The communications and tracking subsystem consists of three separate radio frequency systems: an S-band system, a Ku-band system and an ultrahigh frequency system. Each of these systems uses the hardware being developed for the baseline Space Station Freedom program. A schematic of the system appears in Figure 28.

The S-band system is single-failure tolerant and is used to support voice commands and telemetry between the Space Station and the ground via the Tracking and Data Relay Satellite System. The system is capable of receiving uplink data rates of 72 kbps and of transmitting downlink data at 192 kbps. For Option A-1, the existing Bus-1 Space Ground Link system S-band system will be used until the permanent S-band system is installed on the Space Station. The Ku-band system, which is capable of transmitting 50 mbps, will be available for the human tended phase. A communication outage recorder is included for payload data, providing a minimum of 116 gigabits storage capacity. The ultrahigh frequency system, which is used to support extravehicular activity, is not implemented until the Permanent Human Capability phase.

A wireless system provides the primary means of audio communication, allowing a reduction of the hardwired audio terminal units to only one for each major module. The audio terminal units are used primarily for caution and warning annunciation. Both a hardwired interface to the orbiter and the interface to the Ku-band system that provided audio for video lip synchronization were deleted. The system grows from a zero-failure tolerant to a single-failure tolerant system at Permanent Human Capability. A single audio terminal unit is retained; however, redundancy is provided by the audio terminal units in each of the other modules. Changes to the video system include a reduction in the number of input/output ports, deletion of split-screen processing, and the use of commercial camcorders instead of the currently baselined internal video camera. Because the fixed data system workstations are deleted, there is a need to add a video display device. The liquid crystal display unit being developed for the orbiter is used for this function.

Option A's communications and tracking system is compatible with the ground systems currently being designed for Space Station Freedom. These ground systems will support a Consultative Committee for Space Data Systems communications protocol. If necessary, the redesigned communications and data management system design can be modified to be compatible with currently existing ground facilities which accept data using a time-division multiplexed protocol. Also under consideration is an option to use existing hardware and software that might be available from the orbiter and Spacelab.

Environmental Control and Life Support Systems

The Option A Space Station environmental control and life support system is divided into six functions, defined in Figure 29. The design is based on Space Station Freedom hardware, with design provisions to allow incorporation of existing Russian equipment for on-orbit oxygen generation.

The overall environmental control and life support system accommodations for both the crew and payloads at Human Tended Capability and International Human Tended Capability are the same as the current Space Station Freedom design. In the Space Shuttle-tended operations, the basic life support functions for crew habitability will be provided by the Space Shuttle orbiter, including waste management, potable water supply and extravehicular activity support. When the Space Station is permanently occupied by the crew, these functions will be on board the common habitation module of the Space Station.

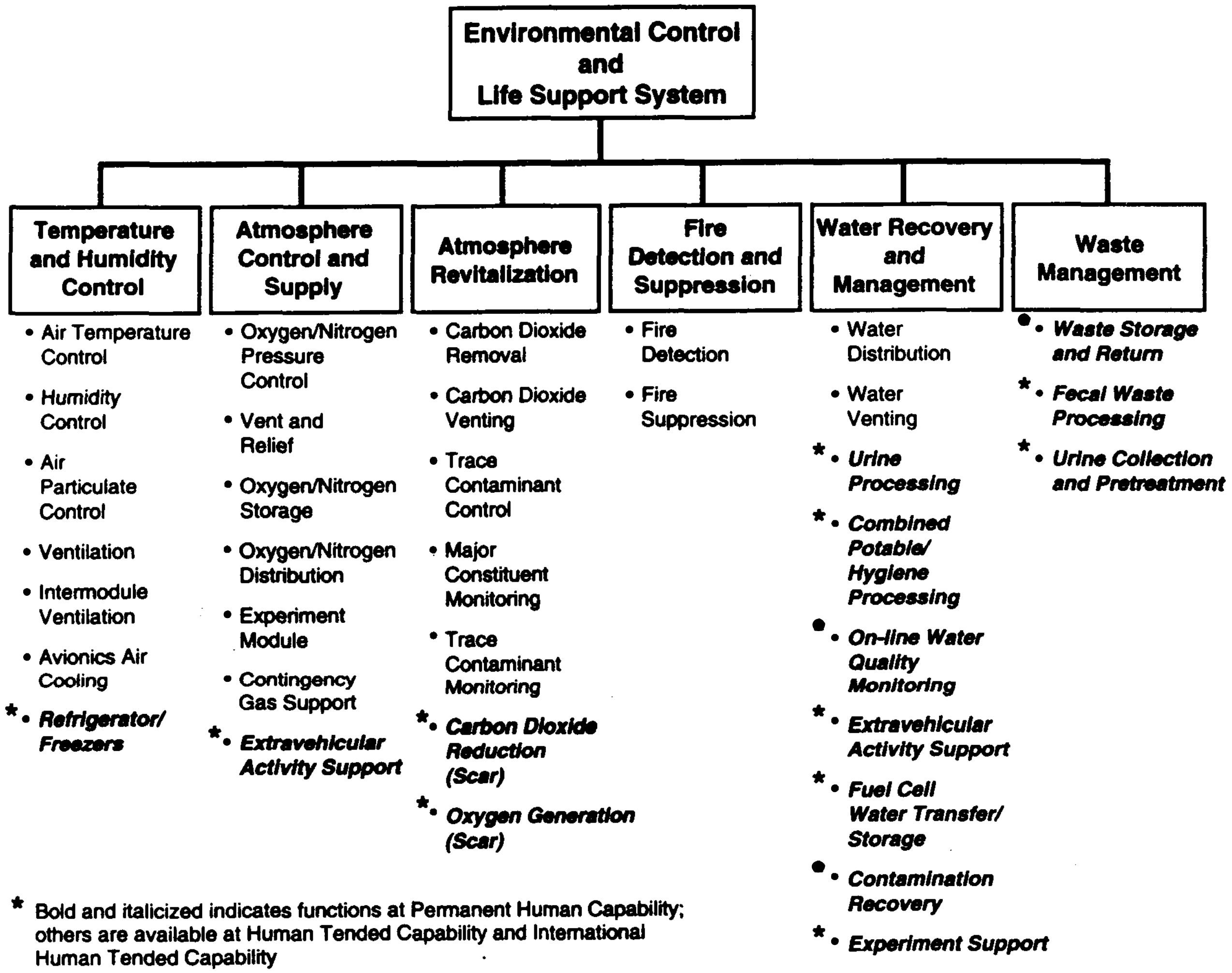


Figure 29
Option A environmental control and life support system functions

The major changes to the environmental control and life support systems design in Option A from the baseline Space Station Freedom are summarized as follows:

- Significant environmental control and life support systems hardware was deleted by using common core-laboratory and common habitation module elements instead of nodes and modules. Deleting hyperbaric operations airlock equipment, including the gas conditioning assembly, simplified the hardware required for extravehicular activity operations. Primary environmental control and life support systems equipment eliminated were the node cabin air conditioning assemblies, tanks, valving, plumbing, and sensors associated with atmosphere supply and control, fire detection and suppression, and air revitalization.
- The approach to meeting failure tolerance for designs at Permanent Human Capability was simplified to:
  - Delete the redundant string of water reclamation and utilize the 1,200 pounds of stored fuel cell water to satisfy life support during maintenance of the single string and the use of the assured crew return vehicles if maintenance cannot be accomplished within 30 days.
  - Delete one rack of temperature and humidity control cabin air hardware in the common habitation module (utilizing maintenance as a leg of

redundancy and orbital replacement units in the redundant temperature and humidity control rack located in the common core-laboratory module).

- Delete one waste management compartment, using maintenance of the remaining unit as a leg of redundancy, and using "Space Shuttle-type bags" and/or assured crew return vehicle as the third leg of redundancy for this two-failure tolerant function.
- Reduce oxygen and nitrogen cryogenic tank requirements and the number of attachment locations on the truss.

All of the above design changes resulted in launch weight savings, savings in development costs for hyperbaric airlock operations, and savings in recurring costs for all of the redundant equipment eliminated. Option A eliminated a total of 3,503 pounds of environmental control and life support systems weight from the Space Station Freedom baseline for Permanent Human Capability.

In addition, Option A reduced the overall environmental control and life support systems power required at both Human Tended Capability and Permanent Human Capability from the Space Station Freedom baseline. A total savings of 208 watts occurred in the Space Shuttle-tended mode, and a savings of 1,993 watts occurred in the permanently occupied mode over the Space Station Freedom baseline. Significant power savings were associated with the elimination of node equipment peculiar to the Option A configuration. However, other power saving features were implemented that could also be implemented in the current Space Station Freedom design or other options being considered in redesign.

A trade between cryogenic storage or gaseous storage of the oxygen and nitrogen consumables showed that the cryogenic storage should be retained, with an option to consider an oxygen-loop regenerative system at Permanent Human Capability. Russian equipment potentially could be used for the oxygen-loop closure equipment (carbon dioxide reduction and oxygen generation). The oxygen-loop closure eliminates oxygen resupply requirements (13,000 pounds per year) at the expense of more environmental control and life support systems power required at Permanent Human Capability.

Flight Crew Equipment Systems

The Option A crew systems are simplified versions of the Space Station Freedom systems. Remaining intact from the Space Station Freedom baseline are the personal hygiene system (shower, waste management compartment, and handwash, oral hygiene and eyewash system), restraints and mobility aids, laundry, galley (oven, refrigerator, trash compactor, nominal and skipped-cycle food storage, drink dispenser and eating utensils), crew health care system and illumination. Deleted from the Space Station Freedom baseline are the film stowage chiller (refrigerator), film cameras and film (personal and operational equipment), and safe haven provisions. Deletions affecting crew systems are the wardroom windows and window workstation provisions, and the hyperbaric airlock capability.

Descoped crew system items include reduced clothing volume (lightweight clothing), interfacing partitions, a maintenance work platform replacing the maintenance workstation, and laptop computers replacing the command and control workstations, element control workstation, and cupola workstation (Figure 30). A dedicated

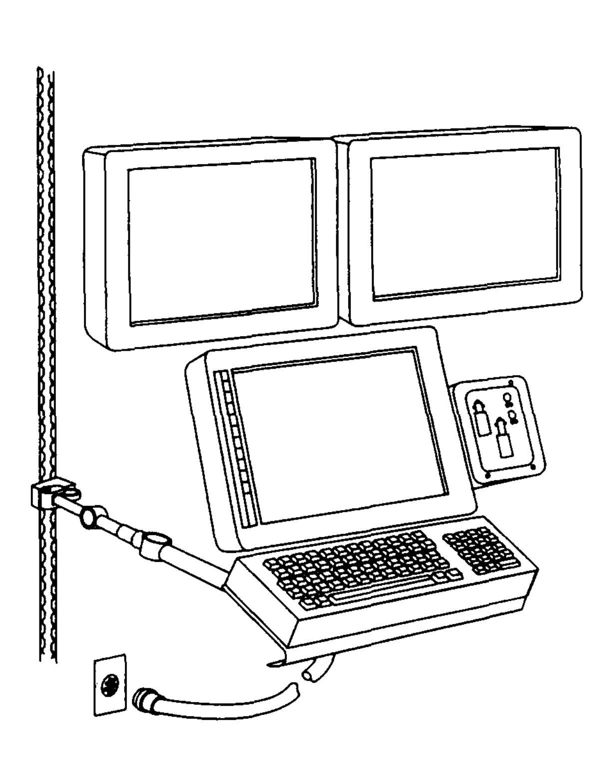


Figure 30
Laptop Workstation

Space Station Remote Manipulator System and Special Purpose Dexterous Manipulator control Space Station for both on-orbit and ground-based operations will be provided. Additionally, the portable emergency provisions, including breathing masks and portable fire extinguishers, were reduced with the elimination of the nodes, while crew systems storage racks in the common habitation module module were reduced in number.

The Space Station Freedom maintenance workstation has been descoped to a lightweight, portable maintenance work platform capable of restraining orbital replacement units, tools and small items such as nuts and bolts (Figure 31). It is provided on-orbit with the common core-laboratory module. Both intravehicular and extravehicular tools are provided at Permanent Human Capability, with the orbiter tools used prior to that time.

Extravehicular Activity System

The crew utilizes the orbiter extravehicular assembly equipment, including airlock, until Permanent Human Capability when they are Space Station-provided. Pressure suits remain the Space Shuttle extravehicular mobility units. The crew and equipment translation assembly cart has been replaced with the simplified supplemental crew and orbital replacement unit for on-orbit transfer and restraint, a manually powered crew translation platform. The portable work platform and articulated portable foot restraint are replaced with existing hardware including the Hubble Space Telescope portable foot restraint and orbiter manipulator foot restraint. Other Space Station Freedom extravehicular assembly system items—including the temporary equipment restraint assembly and tether shuttle—are deleted or reduced in scope, or they are replaced with less complex but similarly functioning items. Crew and vehicle safety are maintained to Space Station Freedom baseline specifications.

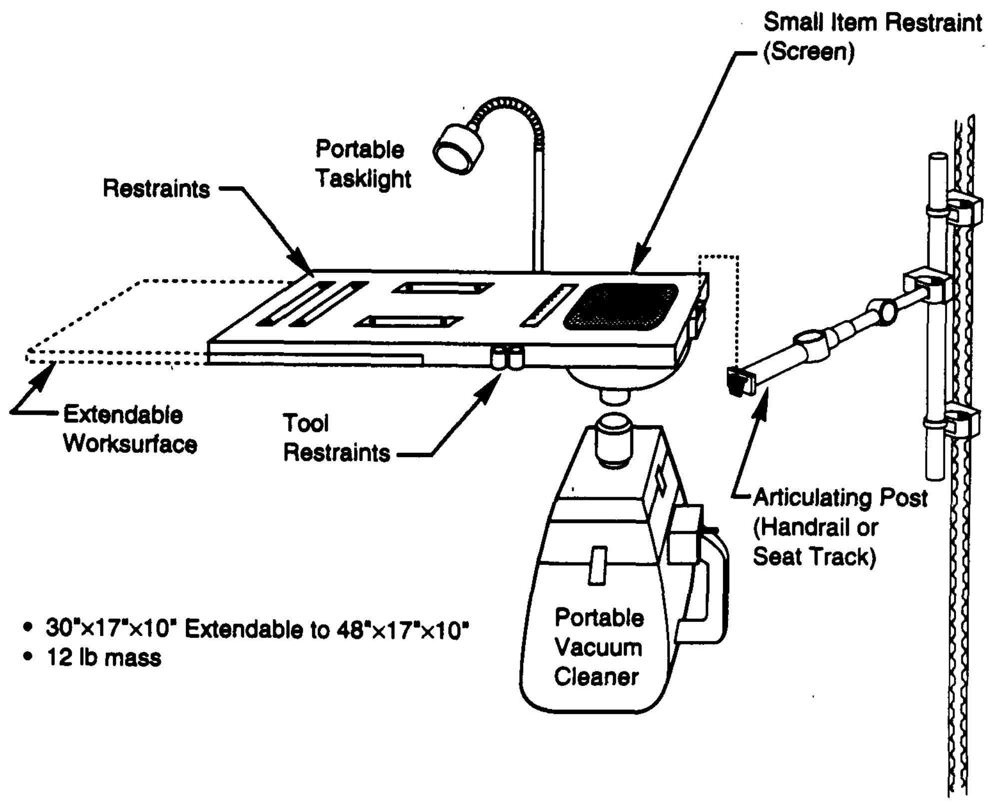


Figure 31
Maintenance platform

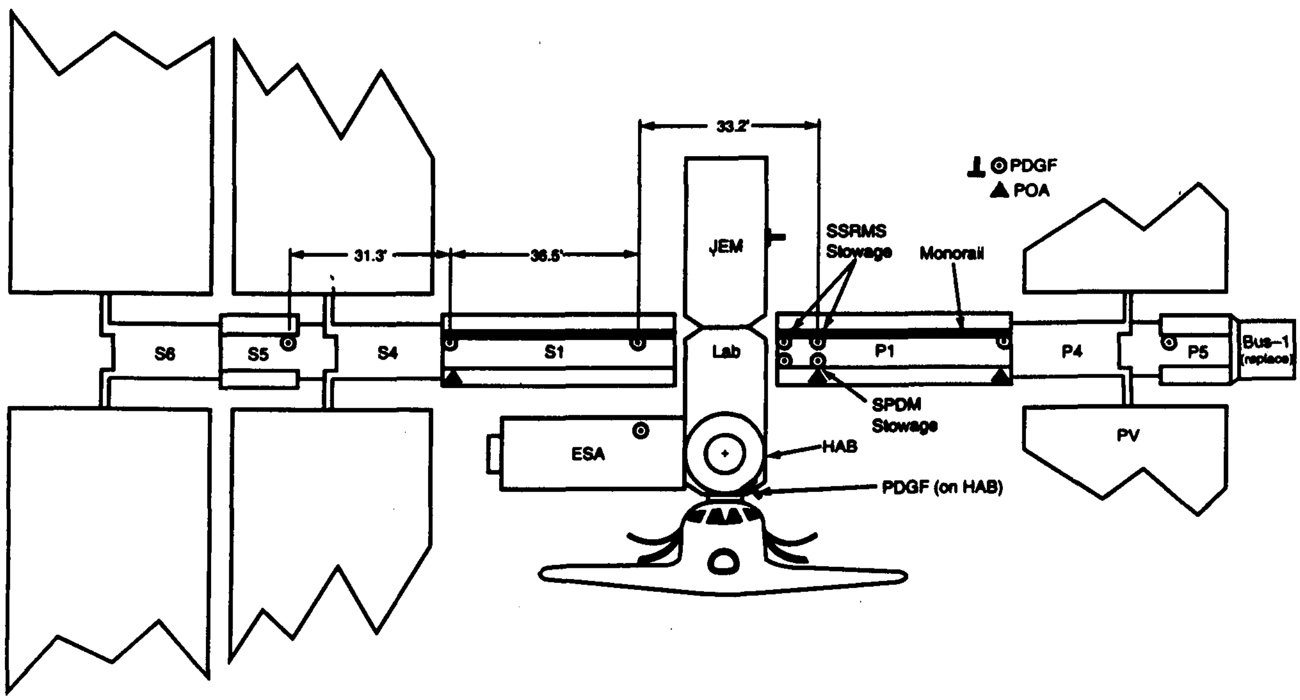
Automation and Robotics

For Option A, the Space Station Remote Manipulator System moves by "stepping" from one stationary power and data grapple fixture to another (Figure 32). Payloads and orbital replacement units, mounted on unpressurized logistics carriers, are transported by the Space Station Remote Manipulator System to the payload and orbital replacement unit accommodation locations on the truss. Orbital replacement units with grapple fixture attachments will be transported to the worksite by the Space Station Remote Manipulator System. All other orbital replacement units will be transported by a device that translates via monorail.

The Special Purpose Dexterous Manipulator attaches to the end of the Space Station Remote Manipulator System. It is used to replace robot-compatible orbital replacement units and eliminates the need for extravehicular activities assistance. Ground control of the Space Station Remote Manipulator System and the Special Purpose Dexterous Manipulator is added to complement on-orbit control capability. This capability can potentially be used to reduce crew intravehicular activity robotic workload.

Manufacturing Considerations

The manufacturing plan for fabrication and assembly of the Option A components and subassemblies utilizes essentially the existing tooling, tool designs and assembly fixtures from the Space Station Freedom program and the Bus-1 program. This includes tooling and fixtures that have been purchased or fabricated for these programs. For example, the common core-laboratory utilizes the same component forming, welding, and subassembly fixtures and tooling used to fabricate the node and laboratory modules. Additional tooling and fixtures are required to accommodate changes made to the common core-



ESA	European Space Agency	PDGF	Power and data grapple fixture
JEM	Japanese Experiment Module	PV	Photovoltaic
ORU	Orbital replacement unit	SSRMS	Space Station Remote Manipulator System
POA	Payload/ORU accommodation	SPDM	Special Purpose Dexterous Manipulator

Figure 32
PDGF / POQ locations for Mobile Service Structure translation and operation

laboratory to adapt to new interfaces, such as the module-to-truss attachment. The same manufacturing facilities and ground support equipment are also utilized, but require adjustments in the integration, assembly and checkout, since there are fewer hardware elements. Integration and checkout of the subsystems in the common core-laboratory differ from the node and laboratory module procedures, using one contractor rather than separate contractors for the node and lab.

Final fit, function and performance checks of the integrated launch packages will be performed at the launch site processing facility at the Kennedy Space Center.

Test and Verification

The verification approach employed for Option A differs significantly from the Space Station Freedom approach in both scope and scale. A considerable portion of the Space Station Freedom verification task addresses verification of distributed systems equipment provided by one work package to another as government furnished equipment. Using a single prime contractor eliminates the need for this verification activity and allows NASA to focus on verification of the flight elements. In addition to this reduction in scope, the Option A design has fewer flight elements, which reduces the scale of the verification task relative to Space Station Freedom. A comparable reduction in scope is achieved in the verification process for International Partner and participant elements. Option A design features, such as core module interface provisions and data management system simplification, reduce the magnitude of the interagency verification activity. That interagency verification activity which remains will be conducted in accordance with the Space Station Freedom plan.

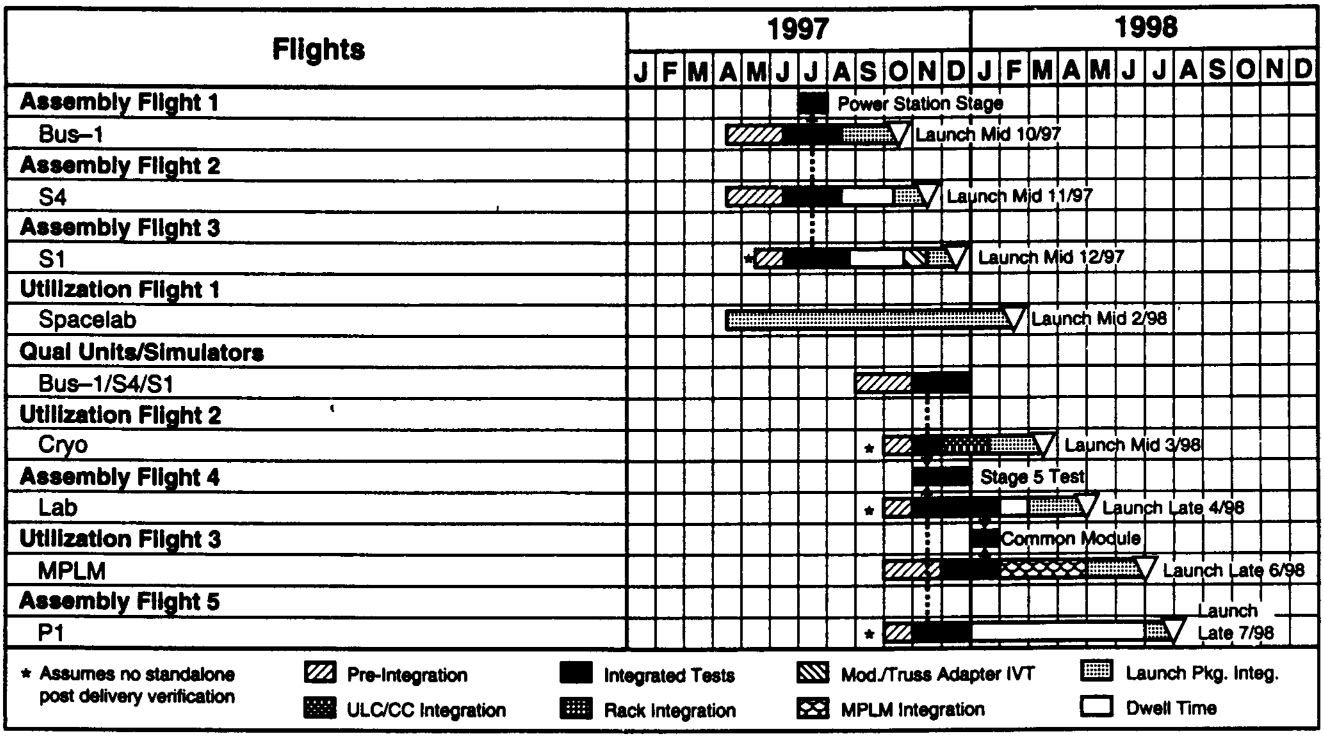
The Option A verification plan for a flight element includes three basic steps: (1) flight element verification is performed on site by the prime contractor encompassing verification of the flight element against element level requirements (i.e., configuration end item specification), (2) verification of integrated flight elements is performed at Kennedy Space Center addressing verification of the interfaces and mutual functionality of interfacing flight elements, and (3) on-orbit checkout verifies the operational readiness of the fielded flight element. NASA takes delivery of the flight element subsequent to successful completion of step 2.

Just as the modular architecture of Option A requires the Space Station to be assembled in stages, it also allows the Space Station to be verified in stages. A hand-off strategy underlies the integrated verification testing. In this strategy, a flight element arrives at Kennedy Space Center and subsequently undergoes integrated testing with flight elements to which it interfaces but that launch on preceding assembly flights. Prior to its launch, this same flight element will undergo integrated testing with interfacing flight elements that launch on succeeding assembly flights. Prior to their launch, these flight elements will in turn undergo integrated flight testing with interfacing flight elements that launch on succeeding assembly flights, and so on. This test flow is shown in Figure 33 for the flight elements comprising the first five assembly flights. Where a flight element launches prior to the arrival at Kennedy Space Center of an interfacing flight element (e.g., the launch of the common core-laboratory prior to delivery to Kennedy Space Center of the Japanese Experiment Module), simulators will be employed in the integrated testing. However, the hand-off strategy also supports verification of simulators. The mini-pressurized logistics module-to-common core-laboratory interface is verified in an integrated test. The physical interface (i.e., berthing mechanism) and a significant portion of the functional interface of the common core-laboratory simulator can subsequently be verified against the mini-pressurized logistics module, prior to usage of the simulator in integrated testing with the Japanese Experiment Module, Attached Pressurized Module, common habitation module, and other pressurized elements, including Soyuz assured crew return vehicles.

Orbiter Modifications

Preliminary assessments indicate that the orbiters used to assemble Option A may create high plume impingement loads on the solar arrays at certain phases of the assembly. Resource estimates have been included for orbiter thruster modifications to minimize the plume loads, and other potential solutions have also been defined or are under study.

The orbiters used with the Space Station at the Power Station phase and Human Tended Capability phases will require extended-duration orbiter modifications for longer stays at the



IVT	Integration verification test	SSRMS	Space Station Remote Manipulator System
MPLM	Mini-pressurized logistics module	UBM	Unpressurized berthing mechanism
PV	Photovoltaic	ULC/CC	Unpressurized logistics carrier/cryo carrier

Figure 33
Testing and launch processing flow

Space Station (20 or more days). However, this study assumed a 20-day maximum orbiter stay-time because of crew limitations, but the orbiter modifications and outfitting currently planned for this capability will suffice.

An external airlock with docking adapter will be required for three orbiters beginning with flights after the Human Tended Capability is achieved. Prior to the Human Tended Capability (flights 1 through 4, Tables 11 and 12), an unpressurized berthing adapter will be used to berth the orbiter to the Space Station elements for assembly and payload operations (Power Station phase). This adapter is a new structure, which is designed to bridge the Spacelab tunnel during the Power Station utilization phase when the orbiter or Spacelab is docked at the Space Station. The adapter provides both power and data interface between the orbiter and Space Station.

Integration Factors

Interfaces have been simplified in Option A by reducing the number of truss segments required for the configuration from that required by Space Station Freedom, and by integrating the functions of the Space Station Freedom modules and nodes into the Option A common modules. Utilization of the Bus-1 guidance, navigation, control and propulsion capabilities will require some modifications of the existing Bus-1 systems to provide compatibility with the Space Station. While significantly fewer in quantity, the technical complexity of element-level interfaces for Option A is comparable to that for Space Station Freedom for the NASA elements. However, in general, the interfaces for the International Partners have been simplified. The electrical and thermal interfaces between the common core-laboratory and the Attached Pressurized Module have been reconfigured to allow internal connectivity, versus the Space Station Freedom method of requiring extravehicular activities for connection. The thermal interface between the common core-laboratory and the Japanese Experiment Module has likewise been reconfigured to allow internal connectivity. The necessity for providing data management system orbital replacement units between Partners has been eliminated.

The Option A command and telemetry system is designed to be compatible with the Space Station Freedom ground system design. If the Bus-1 spacecraft is employed, its command and telemetry system must be used until assembly flight 2; the Bus-1 communications system is not compatible with the NASA Tracking and Data Relay Satellite System and will require interaction with United States Air Force ground facilities.

Option A element development and delivery schedules have been developed to ensure sufficient time is available to support the Space Station launch and assembly. Modifications to the orbiter fleet and the Bus-1 spacecraft can be accomplished in the time available to support the Space Station schedule.

Performance Capability

Weight Summary

Weight estimates were typically developed at the component, subassembly, subsystem, and element levels. Twenty percent margins were allocated on all new items, and a five to ten percent margin was allocated on Space Station Freedom equipments. The final on-orbit weights for each phase are summarized below:

	Option A-1 (pounds)	Option A-2 (pounds)
Power Station	90,000	98,000
Human Tended	132,000	140,000
International Human Tended	344,000	354,000
Permanent Human Capability	480,000	488,000

These totals include the respective buildup and summation of all United States and international elements that make up each phase. Additional weights by flight are shown in Table 11 for both Option A-1 and Option A-2. Launch weight margins for each of the 16 assembly flights for Option A-1 and A-2 are shown on Figures 34 and 35. All of the flights have weight margins in addition to the station and Shuttle manager's reserves of 1800 pounds and 3500 pounds respectively. A summary of weights by subsystem (United States subsystems only) and international elements is reflected in Table 16, including a comparison to Space Station Freedom.

Power Summary

Electrical power available at each Space Station buildup phase is shown in Table 14 for both Option A-1 and Option A-2. The power generated by the solar arrays is shown for two conditions, orbital average and yearly orbital average. The housekeeping power includes station subsystems, assured crew return vehicles (2), cupola, closet module, airlock, orbiter or Spacelab, and the International Partner elements. The power available for payload users is shown for the yearly orbital average condition. At Permanent Human Capability, the power to the users exceeds 30 kW for both Option A-1 and Option A-2. For the two human-tended phases, the power is shown for both the orbiter attached to the Space Station and the Space Station without the orbiter attached. A further breakout of the housekeeping power for the United States systems at the Permanent Human Capability phase is shown in Table 17 for both Option A-1 and Option A-2, as well as a comparison to Space Station Freedom housekeeping power.

Safety and Reliability

General

Option A designs are two-failure tolerant where required to support Space Station survival for the functions of electrical power, data management, thermal control, guidance, navigation and control, and reboost from the Power Station phase onward. For power and thermal control

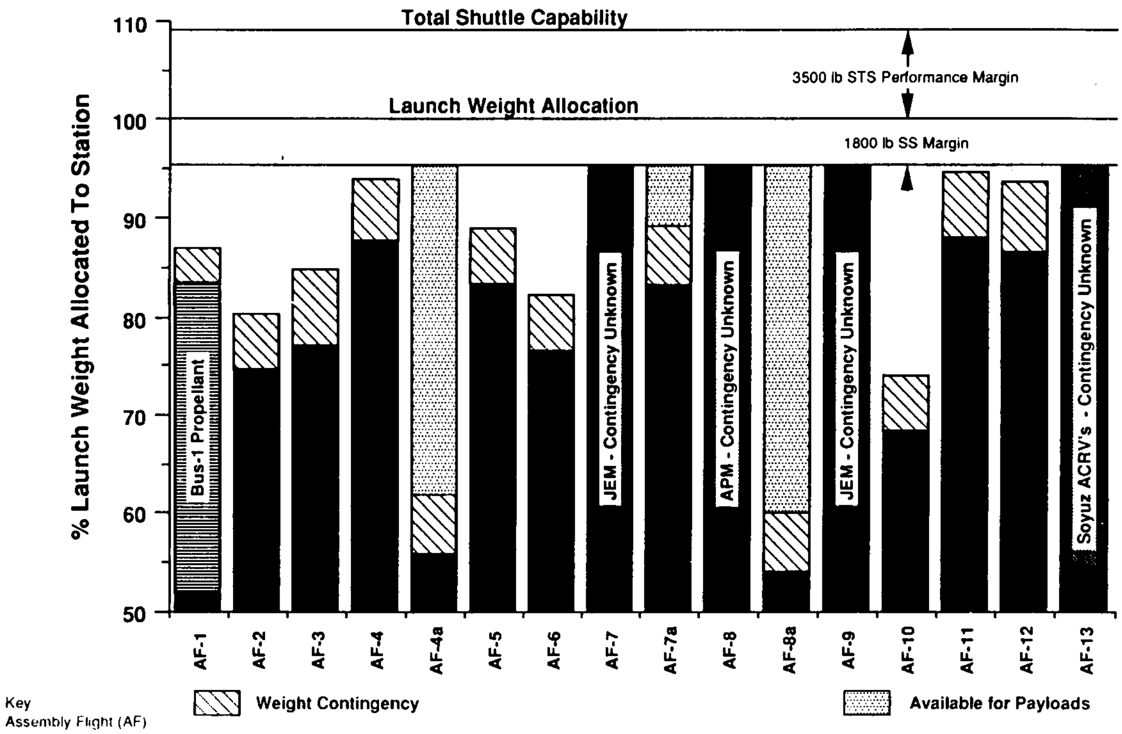


Figure 34
Launch weights for station assembly sequence
Option A-1, 28.8 degree inclination, 220 nautical miles

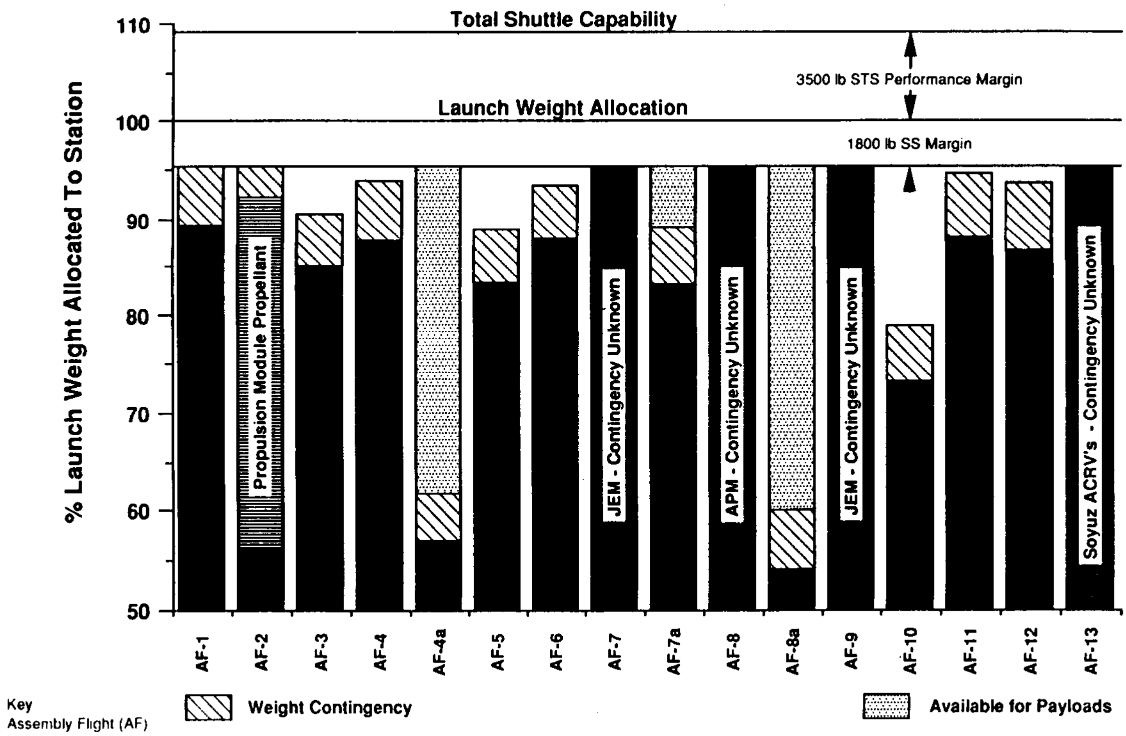


Figure 35
Launch weights for station assembly sequence
Option A-2, 28.8 degree inclination, 220 nautical miles

Table 16
Option A subsystems weight summary

Subsystem	Launch Weight (pound) Space Station *Freedom*	A–1	A–2
Data Management	10,341	6,720	6,330
Electrical Power Generation	34,852	27,700	30,127
Power Distribution and Control	29,193	19,237	14,793
Communications and Tracking	3,323	2,400	2,269
Enviromental Control and Life Support System	19,304	9,266	9,266
Thermal Control	33,399	31,460	28,880
Crew Health-Care System	(Note 2)	1,653	1,653
Crew Systems	10,767	3,621	3,621
Propulsion	29,412	1,755	18,835
Structures	166,623	132,670	143,521
Mechanical Systems	38,418	9,454	9,435
Guidance, Navigation, and Control	2,819	3,444	1,868
Extravehicular Activity	9,202	666	1,176
Utilities	(Note 3)	(Note 3)	(Note 3)
Consumables	30,292	17,140	19,360
Bus–1 Additions	0	1,121	0
Total U.S. Systems Subtotal	**417,945**	**268,306**	**291,132**
Mini-Pressurized Logistics Module	11,639	9,771	9,771
Assured Crew Return Vehicle	17,530	29,693	29,693
European Space Agency	31,405	28,980	28,980
Japanese Experiment Module	58,643	65,260	65,260
Canadian Space Agency	10,841	6,357	6,357
Total	**548,003**	**408,367**	**431,193**

(1) General
- Weights are from SSF Feb. 1993 Level II Resources Margin Summary and from LMSC Bus–1 Data.
- Weights do not include FSE, payloads, nor 1,800 pounds SSF margin per flight.
- "Consumables" includes crew consumables, propellants, and cryos.

(2) Included in man systems weights.
(3) Included in subsystems weights.

Table 17
Option A subsystems power summary
at Permanent Human Capability, without orbiter, United States elements and systems only

United States Systems	Housekeeping Power (kW) Yearly orbital average		
	SSF	Option A–1	Option A–2
Data Management and Applications S/W	3.48	1.82	2.12
Electrical Power Generation	0	0	0
Power Distribution and Control	1.48	0.91	1.07
Communications and Tracking	1.06	1.23	1.23
Environmental Control and Life Support	5.41	3.66	3.66
Thermal Control	1.70	1.98	1.98
Crew Health Care	0.32	0	0
Crew Equipment (Crew Systems)	1.43	1.48	1.48
Propulsion	0.90	0.29	1.24
Structures (Primary and Secondary)	0	0	0
Mechanical Systems	0.20	0.10	0.10
Guidance, Navigation, and Control	0.53	0	1.01
Extravehicular Activity	0.01	0	0
Utilities	0	0	0
Consumables	0	0	0
Miscellaneous	0	0.22	0.22
Margin	0.79	0.58	0.70
Bus-1 (Option A-1)	0	1.11	0
Total	17.31	13.38	14.81

functions, this represents an improvement over the Space Station Freedom design and was achieved by redesign of existing power system hardware and use of cross-strapping between the central thermal control and photovoltaic thermal control systems in the event of failures.

Option A-1 utilizes Bus-1 to accomplish two-failure tolerance for guidance, navigation and control, and propulsion functions, while Option A-2 retains the Space Station Freedom baseline designs for those functions.

The Option A designs have reduced complexity and improved commonality by eliminating several types of orbital replacement units in the data management system and thermal control system. Both the central and photovoltaic thermal control systems now use the same single phase ammonia hardware, totally eliminating all hardware associated with the Space Station Freedom two-phase system. The data management system eliminates all standard data processors, ring concentrators and fiber optic network hardware in favor of a design that uses Space Station Freedom multiplexers and demultiplexers and military standard-1553B data buses. The electrical power system eliminates direct current switching units and battery charge-discharge units. These changes yield simpler designs and eliminate high-maintenance equipment.

The design of nearly all environmental control and life support system hardware is identical to that used on the Space Station Freedom. These designs have been thoroughly reviewed and comply with current reliability requirements. Use of flight-proven Russian hardware is proposed for carbon dioxide reduction and oxygen generation at the Permanent Human Capability phase.

Crew Survival

For crew survival functions, Option A implements the same approach utilized on Space Station Freedom, with the orbiter or assured crew return vehicle providing a third leg of redundancy for non-time-critical failures. Atmosphere control failure tolerance is accomplished early by incorporating two pressure control assemblies in the Option A laboratory module. This, combined with the orbiter, provides two-failure tolerant atmosphere control starting at Human Tended Capability. A third pressure control assembly arrives on orbit with the launch of the Option A habitation module to ensure pressure control, capability even if the laboratory must be isolated due to a contingency. Prior to Permanent Human Capability, air revitalization is provided by the laboratory air revitalization system, atmosphere dilution and the orbiter. At Permanent Human Capability, an additional air revitalization system rack is provided in the habitation module, thereby eliminating the need to dump the atmosphere following failure of the laboratory air revitalization system or following a laboratory isolation event. Option A uses the Space Station Freedom fire protection system to provide automatic fire detection and suppression in the laboratory and habitation modules.

Option A is a modular concept that provides the crew with the capability to isolate an undesired event (i.e., depressurization, contamination or fire) from the other habitable volumes by closing hatches and intermodule ventilation valves.

Assured Crew Return Capability

Capability to return crew members during an emergency is provided by two Soyuz spacecraft, each of which can carry two crew members and medical gear. Both Soyuz spacecraft are attached to the habitation module. They are launched on a single Space Shuttle flight if the station is at a 28.8 degree inclination, and are delivered to the station by the Russian Soyuz launch vehicle if the station is at 51.6 degree inclination.

End-of-Life Safe Disposal

Option A, like the Space Station Freedom, is based on a modular concept that facilitates end-of-life safe disposal by utilizing the Space Shuttle to return modular segments to Earth.

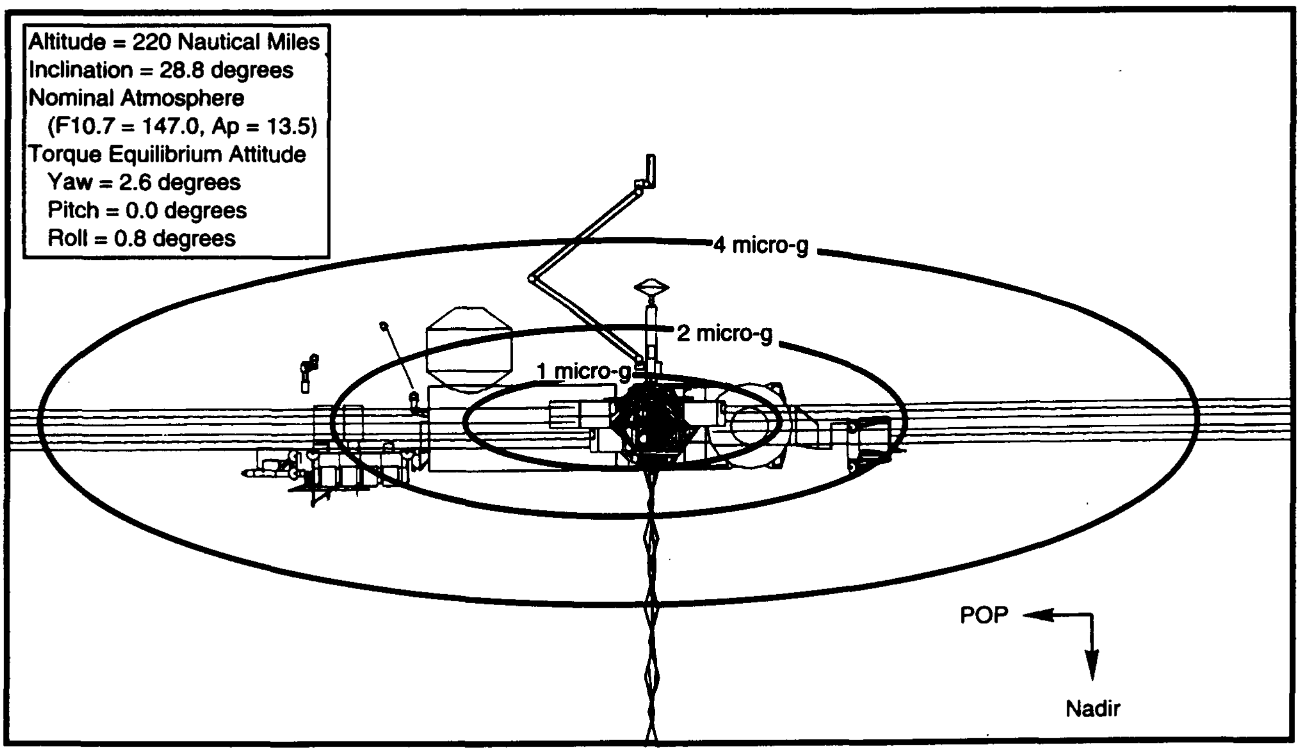
Resources Available to Users

A major goal of the Space Station redesign activity is to ensure that any new design or modification of the existing design adequately accommodates a wide array of microgravity sciences, life sciences and other sciences in internal and external attached payloads. Particular importance was assigned to the accommodation of microgravity sciences and life sciences payloads which require a long-term, stable microgravity environment.

A very important goal of space research and development is to characterize the effects of space on organisms, particularly humans. Option A provides a long-term, stable, low-gravity environment and up to 12 kW provided to some user racks. In addition, payload accommodation resources such as power and volume are provided in the three laboratory modules capable of adequately accommodating life sciences research and development, including a centrifuge. Moreover, provisions are made at Permanent Human Capability to accommodate a life sciences mini-laboratory, including a centrifuge module and supporting life sciences hardware.

During the Power Station phase of Option A assembly, the Space Shuttle and Spacelab provide an on-orbit research capability to accommodate up to eight equivalent double racks of microgravity materials processing, life sciences investigations and other science experiments for extended operations of up to 20 days. These orbiter and Spacelab flights utilize the early Space Station elements primarily as a source of power and attitude control. The orbiter and Spacelab together provide all other necessary functions required to operate payloads.

When the orbiter is not docked, the microgravity profiles are good throughout the assembly sequence. During Human Tended Capability, the entire common core-laboratory is within one-microgravity or less. During International Human Tended Capability, when the Japanese Experiment Module, Columbus Attached Pressurized Module, and common core-laboratory are all operational, all laboratories are within the two-microgravity zone, with the majority of laboratory space lying within the one-microgravity zone, as shown in Figures 36 and 37. When the orbiter is docked, the Space Station is skewed in orientation and the microgravity degrades. When the orbiter is docked at Human Tended Capability, the common core-laboratory is within a four-microgravity zone, and at International



POP—Perpendicular-to-Orbit Plane

Figure 36
Option A microgravity zones at International Human Tended Capability (view 1), arrow mode, without orbiter

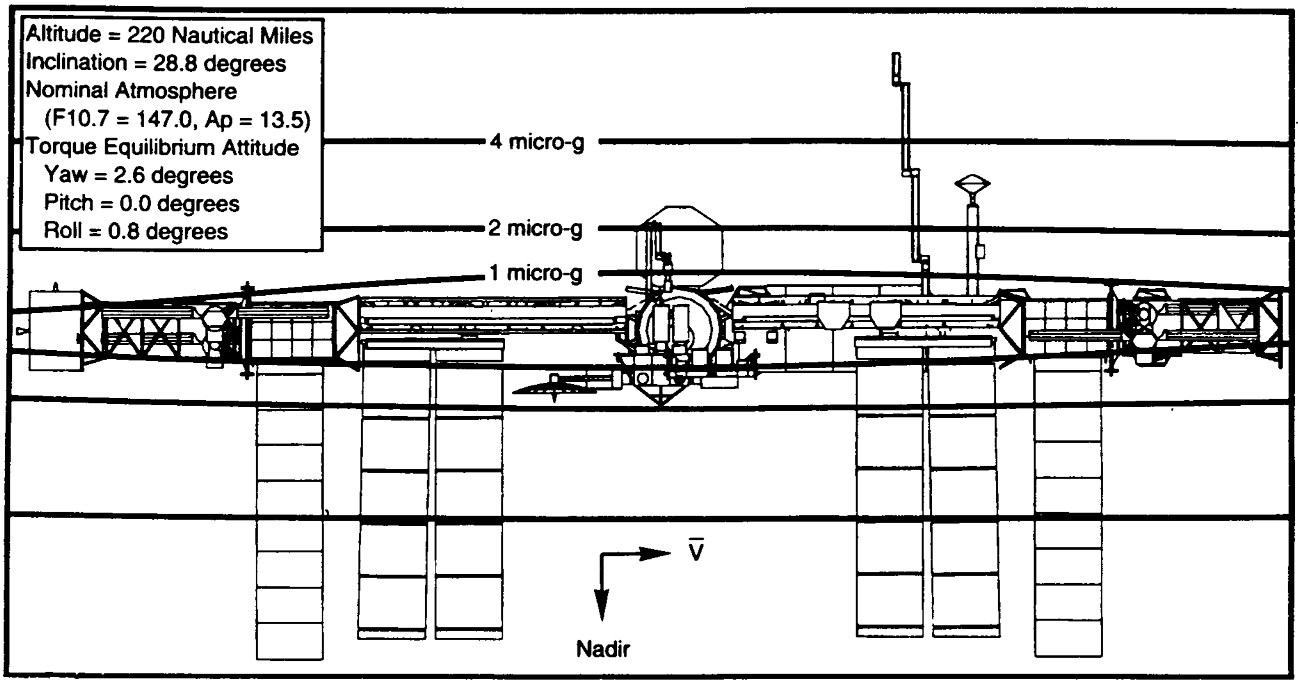


Figure 37
Option A-1 microgravity zones at International Human Tended Capability (view 2), arrow mode, without orbiter

Human Tended Capability, the majority of all three laboratories are within the four-microgravity zone, with portions of the Japanese Experiment Module extending outside that zone. It is anticipated that configurations can be adjusted to improve microgravity environments.

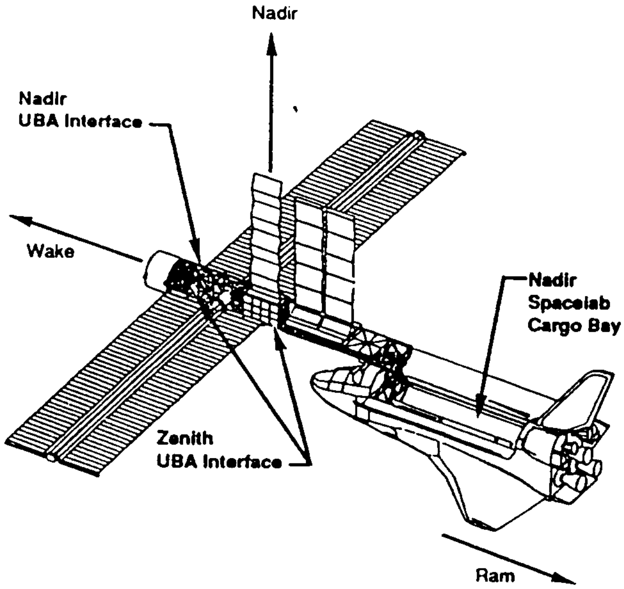
Attachment locations for external payloads are provided on the nadir and zenith sides of the truss at the unpressurized berthing adapter locations (Figures 38 and 39). Other possible payload attachment locations are also shown on these figures. Viewing in the ram and wake directions is achieved by proper orientation of the payloads mounted at these locations. Additional external mounting locations are provided on the Japanese Exposed Facility (10 sites). An eight-inch diameter optical quality scientific window is provided in a hatch located on a radial port in the habitation module in Option A-1 and in the end of the closet module in Option A-2 at Permanent Human Capability. A similar window is provided in a radial port hatch in the laboratory for both Options A-1 and A-2, but this window is later covered by the cupola upon its delivery to the Space Station. Earth sciences payloads can use the windows and external mounting locations. Astronomy and astrophysics payloads can also use external mounting locations.

Payloads can be operated during times when the Space Station is occupied and unoccupied, at all buildup stages. Utilization missions are flown between Space Station assembly and logistics flights. The four standard phases of Option A buildup offer plateaus at which Space Station operation and utilization can continue for a while before proceeding to the next phase. If such an operation were planned to continue for any length of time at a given plateau, the Space Station could be optimized for operation at that plateau.

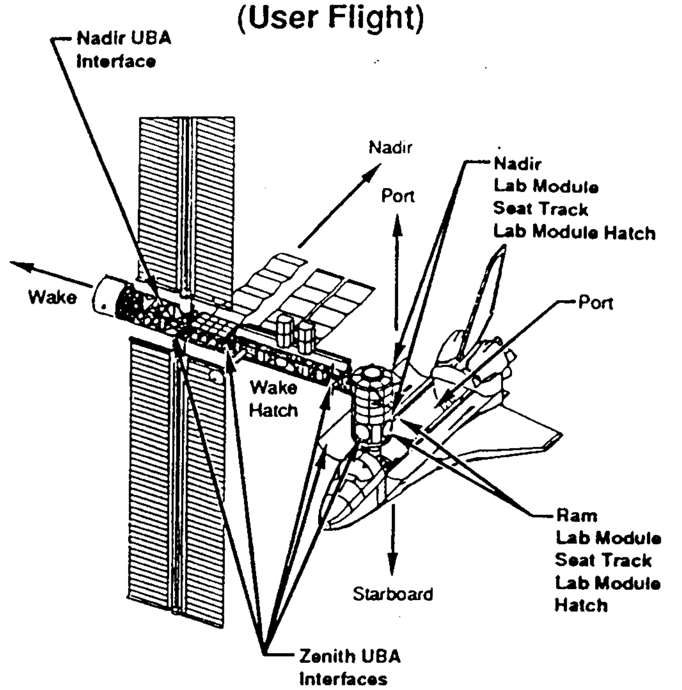
Experience gained from operations of Spacelab payloads has shown that payload volume, crew time, power and payload consumables are major factors in accommodating research and development payloads on space vehicles. Other important and often critical factors to particular experiments are communication links, video, venting and microgravity levels.

Option A provides nine user racks at the Human Tended Capability phase and a total of 39 user racks with the addition of the two International Partners' laboratories. Reduction

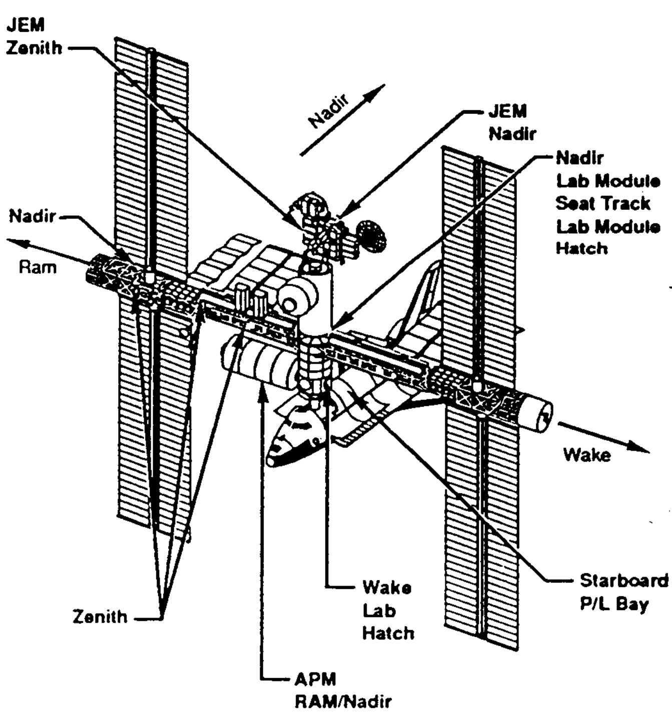
A–1 Power Station (Assembly Flight 3)



A–1 Human Tended Capability (User Flight)



A–1 International Human Tended Capability (Assembly Flight 12)



A–1 Permanent Human Capability (Assembly Flight 16)

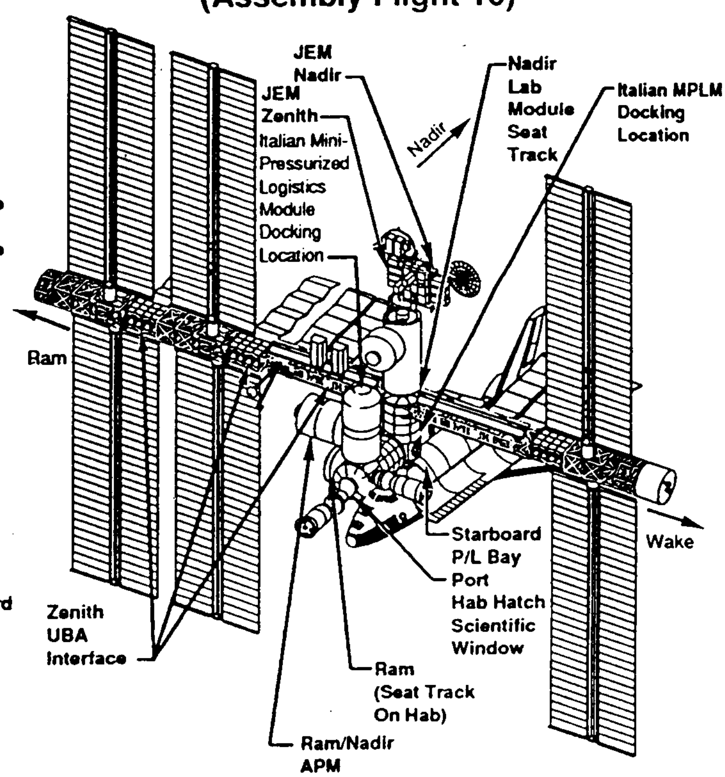
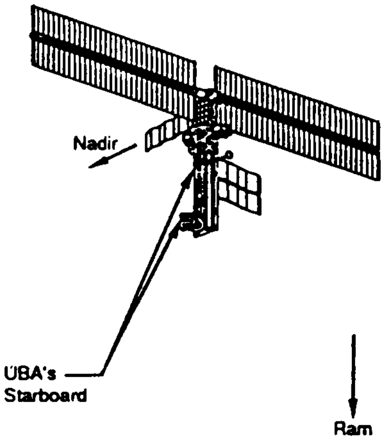
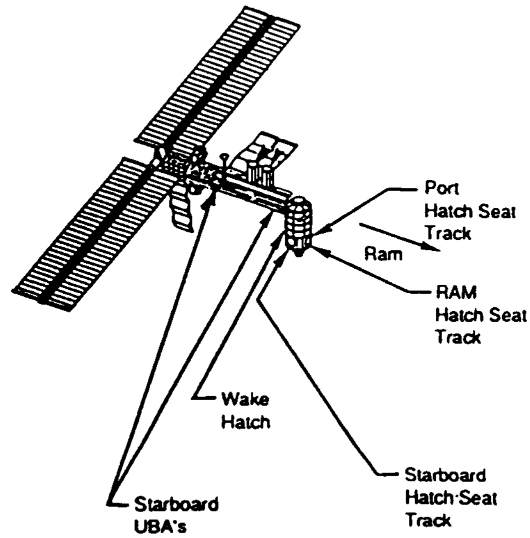


Figure 38
Option A-1 candidate attached payload locations

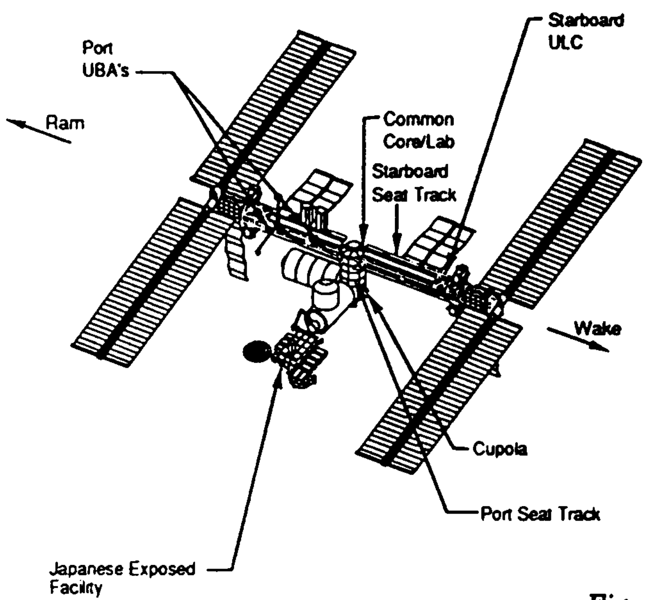
Power Station
20 Kilowatts (kW) 3 Assembly Flights
On-Orbit Mass = 98 klb



Human Tended Capability
20 Kilowatts (kW) 4 Assembly Flights
On-Orbit Mass = 140 klb



International Human Tended Capability
40 Kilowatts (kW) 12 Assembly Flights
On-Orbit Mass = 488 klb



Permanent Human Capability
60 Kilowatts (kW) 16 Assembly Flights
On-Orbit Mass = 354 klb

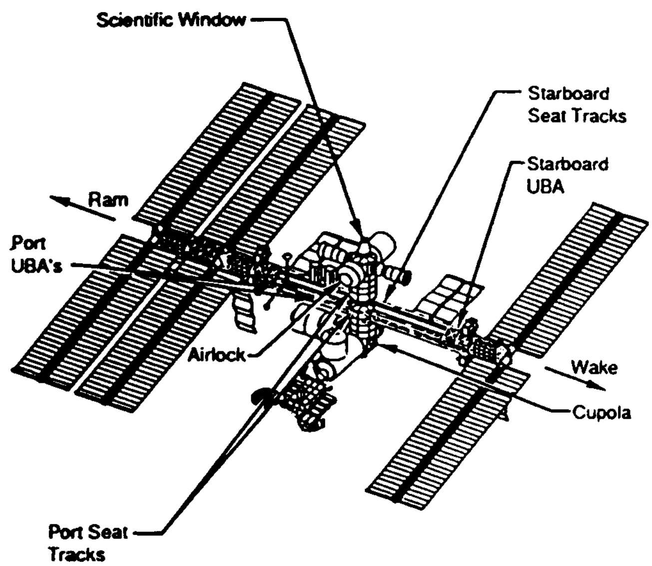


Figure 39
Option A-2 candidate attached payload locations

in both external and internal maintenance and simplification of systems enable Option A to provide approximately 7,000 hours per year of crew time to support user activities. Both Option A designs provide a substantial increase in average payload power as compared to present Space Shuttle and Spacelab missions. The user power comparison for Option A-1 is shown in Figure 40; data for Option A-2 is nearly identical. Option A provides user downlink capabilities of 43 megabits per second. A communication outage recorder with a 116 gigabits storage capacity is provided. Users are also provided a laboratory equipped with an acceleration mapping system, user refrigerator and freezer, pressurized nitrogen gas, potable water, the capability to vent waste gas, both liquid and air payload cooling, and a vacuum source. An eight-inch optical quality window is provided on an available or unused hatch. At Permanent Human Capability, approximately 20 percent of user racks in the three laboratories are within a one-microgravity level, approximately 92 percent are within a two-microgravity level, and all of the user racks are within a four-microgravity level. Provisions to mount external, attached payloads in ram, wake, nadir and zenith are provided at 14 locations at Permanent Human Capability

Accommodation of International Partners

International Partners and participants with NASA in the Space Station Freedom program are

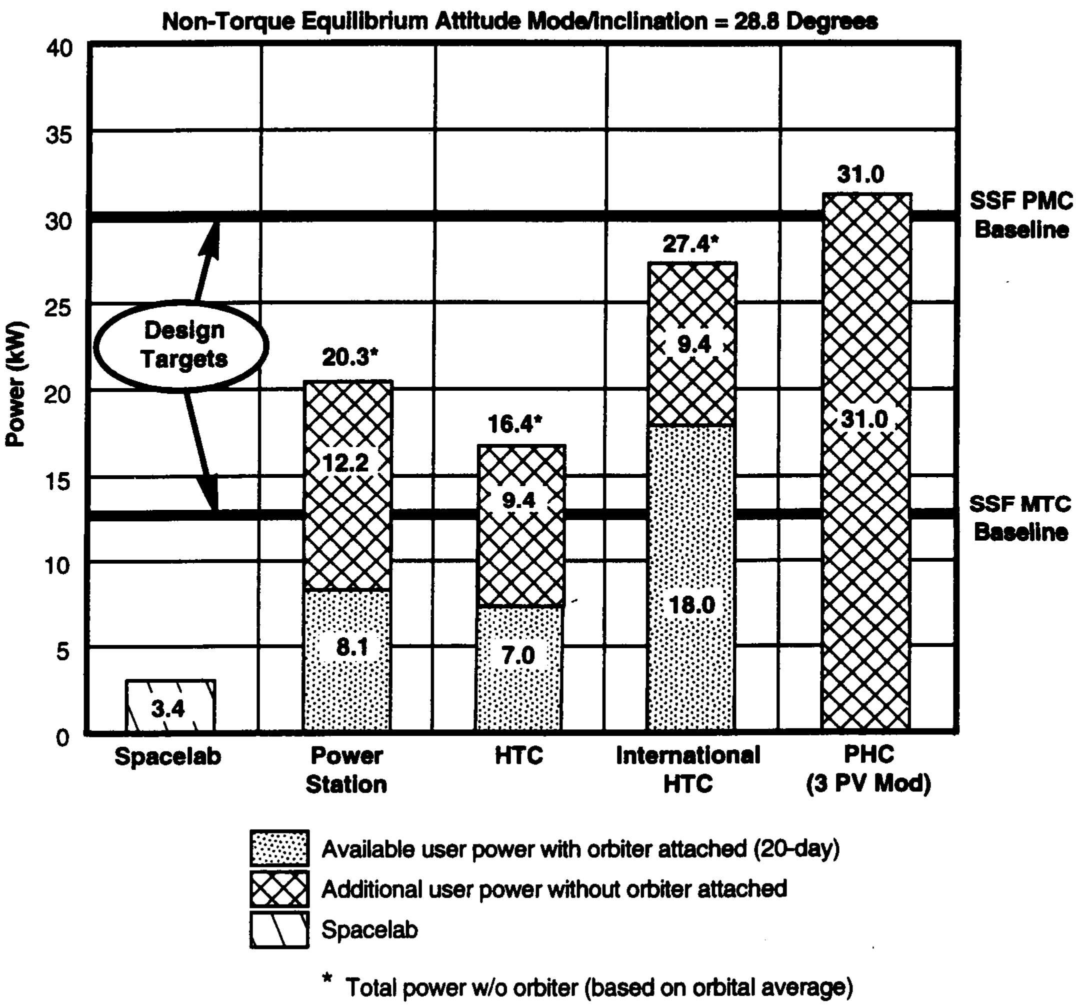


Figure 40
Option A-1 available payload power comparison

the National Space Development Agency of Japan, the European Space Agency, the Canadian Space Agency and the Italian Space Agency.

The Option A station configuration preserves both the functions of elements provided by International Partners and, with minor exceptions, their elements' hardware and software interfaces to the NASA elements, including agreed-to intersite deliverables. For instance, International Standard Payload Rack interfaces, as specified in the International Standard Payload Rack for NASA-European Space Agency-NASDA Modules interface control document, are unchanged with the exception of modification to the data interface. The changes required in the other multilateral interface control documents are similarly small in scope, preserving to the maximum extent the existing Space Station Freedom interfaces. For instance, the addition of the Italian Space Agency-provided closet module will not impact the interface of the mini-pressurized logistics module; the interface of the closet module to the common habitation module will be an adaptation of the mini-pressurized logistics module to common core-laboratory interface, building upon the existing Space Station Freedom interface definition for the mini-pressurized logistics module. Where interfaces have been revised, significant effort has been made to ensure that the revised interface is simpler or otherwise improved over the Space Station Freedom design.

Option A potential impacts to International Partners can be summarized in the following four categories: (1) utilization and payload resources; (2) attachments and interfaces; (3) location and orientation; and (4) schedule. The impact on each International Partner for each of these categories are summarized in Table 18.

One primary impact has been identified under the "attachments and interfaces" category. Specifically, the interface for the Canadian Space Agency's Mobile Servicing System has changed as a result of the deletion of the NASA-provided Mobile Transporter. This impacts the manner in which the Canadian-provided Space Station Remote Manipulator System and Special Purpose Dexterous Manipulator interface with the truss. These changes, as well as changes in the specific tasks which the Mobile Servicing System has to accomplish, have been coordinated with the Canadian Space Agency to establish the technical feasibility of the Option A design.

Likewise, changes in the thermal and electrical power interfaces between the NASA elements and the Columbus Attached Pressurized Module have been coordinated with the European Space Agency for technical feasibility. The result of this coordination was incorporation of primary power feed through and thermal control heat exchangers on the common core-laboratory module; this interface change allows the Columbus Attached Pressurized Module to be mated to the Space Station without any planned extravehicular activity. A similar change on the thermal control system has been discussed with the National Space Development Agency of Japan and incorporated in the core module to Japanese Experiment Module interface. Pending resolution of power equipment location in either the Japanese Equipment Module or the common core-laboratory module, a similar change in the primary power feedthrough could also be implemented. This interface change is considered beneficial by both the European Space Agency and the Japanese Space Agency, and results in a minor technical impact for the common core-laboratory. Additionally, the Option A data management system design does change the data management system interface with the Columbus Attached Pressurized Module and the Japanese Experiment Module. The data management system changes have been discussed with the International Partners, but require further review and coordination.

Growth Capability

The Option A design is a modular design and lends itself well to growth, with the environmental control and life support system sized initially for a crew of eight. If long-term larger crew sizes require growth of the Space Station pressurized volume, the first module to be added would be a second habitation module, which would be followed by a second United States laboratory module and a fourth photovoltaic module. The additional 20 kW of power would be required to support the additional capability provided by the new modules.

The second habitation module would provide the crew with a new "quiet" module that contains sleep compartments for eight, a second galley, a second toilet, a window, a second shower, additional stowage, and additional refrigeration and freezer capability. The new laboratory would

Table 18
Summary of Option A impacts on International Partner Memorandums of Understanding

International Partner / Impact Category	Canadian Space Agency (CSA)	European Space Agency (ESA)	National Space Development Agency of Japan (NASDA)	Italian Space Agency (ASI)
Utilization/ Payload Resources	Slight reduction in payload volume Slight reduction in payload available power and data services	Slight reduction in payload available power and data services	Slight reduction in payload available power and data services	Slight reduction in payload volume Slight reduction in payload available power and data services
Attachment Interface	U.S.-provided mobile transporter eliminated. Method of attachment of CSA's SSRMS has changed	Core interface provisions by NASA Laboratory to APM. Slight impact from DMS simplification	Slight impact from DMS simplification	No impact
Location/ Orientation	No impact	No impact		No impact
Schedule	Delivery schedule for CSA elements has been relaxed	Delivery schedule for ESA elements remains unchanged	Delivery schedule for NASDA elements remains unchanged	U.S. will exercise option for Mini-Lab. MPLM's increased by 4 racks. Provide a new closet module. Provide an additional MPLM.

* Occasional re-orientation of the space station assembly to maximize power generation

CSA Canadian Space Agency
SSRMS Space Station Remote Manipulator System
APM Attached pressurized module
DMS Data management system
ESA European Space Agency
NASDA National Space Development Agency of Japan
MPLM Mini-Pressurized Logistics Module

increase the number of experiment slots for the user community.

The growth of Option A-1 would be accomplished by placing the two new common modules on the port and starboard radial ports of the habitation module and mounting the displaced assured crew return vehicle and the airlock on the radial ports of the new modules. For both options, the fourth photovoltaic module would be added to the port side of the truss in the same fashion as the third array was added to the starboard side.

Potential Cost Saving Features

The following Option A design approaches resulted in cost savings relative to Space Station Freedom:

- Delete five truss sections on Option A-1; delete three truss sections on Option A-2.
- Use common modules instead of different modules and nodes; use a "core" module outfitting approach for the laboratory.
- Use the stretched mini-pressurized logistics module, and delete the United States pressurized logistics module.
- Reduce overall orbit replacement units by approximately 30 percent.
- Delete the battery charge and discharge unit, the direct current switching unit and the large rotary alpha joint.
- Delete the two-phase thermal control system.
- Simplify the atmosphere control and supply, and the temperature and humidity control system.

- Use Russian equipment to close the oxygen loop.
- Delay the airlock until Permanent Human Capability.
- Use the Bus-1 to provide all guidance, navigation and control, and propulsion functions on Option A-1.
- Simplify the data management system to multiplexer and demultiplexer-based 1553B data bus using a simplified table-driven software architecture.
- Reduce audio and video components.
- Delete mobile transporter—incorporate small, simple extravehicular activity cart and monorail
  - Space Station Remote Manipulator System moves by "stepping" from one stationery power and data grapple fixture to another

The following is a list of the major items which were considered, but **were not implemented** in the Option A final design.

- Use orbiter airlock only (no Space Station airlock)
- Delete Space Station cupola
- Use dual orbiters for assured crew return capability
- Use orbiter Ku-band only (no Space Station Ku-Band)
- Incorporate Space Station alpha joint
- Incorporate Space Station mobile transporter
- Replace ammonia external thermal control system with orbiter coolant system
- Use Spacelab high-rate multiplexer and data recorder
- Use Spacelab data management system
- Use orbiter video system
- Locate Bus-1 (Option A-1) reaction control thrusters on extension booms
- Delete passive dampers from Option A-2
- Incorporate integrated propulsion modules in Option A-2 at 51.6 degree inclination
- Delete DC to DC converter unit in electrical power system
- Change Space Station voltage distribution system to 28 volts DC

In addition to the hardware items listed, two flight schedule options were considered for bringing the habitation module up early in the assembly sequence. One option attached the habitation module to the Space Station before the international laboratories were launched, and the second option brought up the habitation module between the two international laboratory launches.

Option-Specific Operations

Flight and Ground Operations

Option A-1 uses the Bus-1 vehicle for propulsion and guidance, navigation and control functions. For the first two assembly flights, communications to the assemblage are through the United States Air Force Space Ground Link System. After that, the primary communications path is through the Space Station S-band communications system as relayed through the Tracking and Data Relay Satellite System. For the A-2 option, the Space Ground Link System is not used. For both A-1 and A-2, the payload high-rate data is transmitted with the Space Station Ku-band communications system.

For the Power Station configuration, payload operations occur during periods with and without human presence. All human-tended operations will be Space Shuttle and Spacelab based. The Power Station housekeeping operations consist of attitude stabilization, thermal protection, and ground controlled reconfiguration, reboost and redundancy management. A "safe mode" capability in the flight system permits minimal ground monitoring. The ground control facility is a minor modification to the Space Shuttle Control Center. The Space Station Control Center and the Space Station Verification Training Facility are deleted. Payload operations are through the Spacelab Payload Operations Control Center. Sustaining engineering and logistics support are designed to be consistent with the dramatically reduced set of flight hardware components.

For the Human Tended and Permanent Human Capability phase of Option A-1 and Option A-2, the basic functions provided for will be similar to the Space Station Freedom program. Due to reductions in flight hardware for both Options A-1 and A-2, significant reductions in extravehicular activity maintenance occur. The Bus-1 option has the greatest reduction because it is a single, highly-redundant orbital replacement unit with a resulting high reliability and with a maintenance approach that requires replacing the entire Bus. Command and control are through the Space Station Control Center, with payload operations occurring through the Payload Operations Integration Center. It is assumed that Bus-1 training and management support will be through a Space Station project office that will work with the United States Air Force project office and the contractor, Lockheed Missiles and Space Company, to provide procurement, development and all other Bus-1 unique costs, and no special Space Station program provisions are made for classified data handling. Space Station systems training uses the Space Station Verification and Training Facility, and the Payload Training Complex is used for payload training. Consistent with the general operations cost reductions, the training focuses on high fidelity nominal operations with limited contingency training, except where flight safety is involved. The 24-hour safe mode greatly reduces the team sizes for Control Center and training activities. The planning template is also shortened to further reduce the ground staffing.

Ground processing is similar to the baseline Space Station Freedom program except for the handling of Bus-1, which in turn eliminates the need for the baseline processing of propellant modules. The utilization of Bus-1 and Bus-1 ground support equipment in Option A-1 will not change the functional operations to be performed at the launch site. The assumption of "hands on" responsibility for Bus-1 processing by Lockheed Missiles and Space Company and Kennedy Space Center in a "host" role is a departure from past Space Station planning, in which Kennedy Space Center has "hands on" responsibility for all United States Space Station elements. Under the current assumptions for Option A-1, Lockheed Missiles and Space Company performs the Bus-1 post-delivery verification test in the Space Station Processing Facility. Kennedy Space Center then performs Bus-1 to Space Station physical integration, functional interface demonstration tests, and simulated Space Shuttle interface verification tests, with Lockheed Missiles and Space Company support for Bus-1 activities. After these activities in the Space Station Processing Facility, the Bus-1 is transported to a hazardous processing facility for propellant loading by Lockheed Missiles and Space Company. After propellant loading, the Bus-1 is installed in a canister for transporting to the launch pad and installation into the Space Shuttle for launch. As more data becomes available for the Bus-1 program, allocation of responsibilities between Lockheed Missiles and Space Company and Kennedy Space Center may need to be revised. Prelaunch and postlanding operations for Option A-2 are reduced, but not functionally different than those planned for Space Station Freedom.

Sustaining engineering and program management are similar to the general reductions covered in the Operations section of this report. For Bus-1, these services would be obtained through the United States Air Force.

Logistics and Utilization Flights

Logistics and utilization flights supply the experiments and material required to utilize and maintain the Space Station. Delivered supplies include crew systems, user items, spares and fluids. Utilization flights occur during the Space Station assembly phase and mark the beginning of payload crew operations. Logistics and experiments are manifested on three different logistics carriers which are then placed in the orbiter payload bay for delivery to the Space Station. Pressurized cargo is delivered in a stretched version of the mini-pressurized logistics module which will be designed to carry 12 racks (the current mini-pressurized logistics module from the Space Station Freedom program carries eight). The racks are exchanged on orbit; used racks are returned to Earth. The unpressurized logistics carrier accommodates a wide variety of items from cryogenic fluid bottles to unpackaged spare parts. For Option A-2, propellant is delivered in the propulsion modules, which are basically unitized propulsion systems that will be refilled and refurbished on the ground and cycled back to the Space Station. Option A-1 propellant resupply is achieved by replacing the Bus-1. The unpressurized logistics carriers and propulsion modules are the designs used by the Space Station Freedom program.

The utilization, logistics and outfitting flight schedule and manifest for Option A-1 assembly phases is depicted in Table 19. The data include usable payload for science and any other hardware or consumables that are required by the Space Station as secondary cargo, but the majority of each utilization flight is payload-related.

Table 19
Utilization, logistics and outfitting flights for Option A-1 at 28.8 degrees inclination, standard external tank, no advanced solid rocket motor

Flight	Weight (lb.)* Pressurized	Weight (lb.)* Unpressurized	Item
UF–1	$\boxed{10{,}400}$		Spacelab Racks
	14,700		Spacelab Long Module
		5,770	Overhead
		$\boxed{5{,}830}$	User Available
UF–2		11,060	O2/N2 Cryo Carriers
		3,646	ULC Tare Weight
		2,646	Overhead
		$\boxed{19{,}348}$	User Available
AF–4A	7,200		6 U.S. Lab Outfitting Racks
	$\boxed{5{,}000}$		5 User Consumables Racks
	8,700		12 Rack MPLM Tare
		4,174	Overhead
		3,661	SSRMS
		$\boxed{6{,}965}$	User Available
UF–3	3,600		3 U.S. Lab Outfitting Racks
	$\boxed{8{,}000}$		8 User Consumables Racks
	8,700		12 Rack MPLM Tare
		2,134	Overhead
		$\boxed{13{,}266}$	User Available
LF–1		29,310	Bus–1
		3,800	Cupola
		2,098	Overhead
AF–7A	6,000		5 JEM System Racks
	6,000		5 JEM ISPR's
	$\boxed{1{,}000}$		1 User Consumables Rack
	8,700		12 MPLM Tare
		3,174	Overhead
		5,530	Cryo Carrier
		3,646	ULC
		$\boxed{1{,}650}$	User Available
LF–2	$\boxed{6{,}000}$		6 User Consumables Racks
	8,700		MPLM Tare
		11,060	O2/N2 Cryo Carriers
		3,646	ULC Tare Weight
		3,174	Overhead
		$\boxed{3{,}120}$	User Available
AF–8A	12,000		9 APM Outfitting Racks
	$\boxed{1{,}000}$		2 User Consumables Rack
	8,700		MPLM Tare
		2,134	Overhead
		$\boxed{11{,}866}$	User Available
UF–4	$\boxed{13{,}200}$		11 User Racks
	8,700		MPLM Tare
		2,134	Overhead
		$\boxed{11{,}666}$	User Available

AF Assembly Flight
APM Attached Pressurized Module
JEM Japanese Experiment Module
ISPR International Standard Payload Rack
LF Logistics Flight
MPLM Mini-Pressurized Logistics Module
SSRMS Space Station Remote Manipulator System
UF Utilization Flight
ULC Unpressurized Logistics Carrier
ASRM Adavanced Solid Rocket Motor

$\boxed{}$ User item (Note: Terminology for "assembly," "utilization," "logistics," etc., is compatible with SSF)
*1,800 pounds Space Station *Freedom* Program margin not held in reserve.

At Permanent Human Capability, five to six Space Shuttle flights are required to supply the facility each year at 28.8 degrees. Using either the advanced solid rocket motors or aluminum lithium external tanks would reduce this requirement to four or five flights per year. Option A-1 uses the 12 rack mini-pressurized logistics module for four flights (carrying two modules on one of the flights), co-manifesting unpressurized cargo (cryogenic oxygen and nitrogen plus attached payloads and spares) on two of these flights. Every two years, a fifth flight is required to carry a replacement Bus-1, co-manifested with unpressurized cargo. Option A-2 uses a similar flight sequence, except that the 12-rack mini-pressurized logistics module flies on all five flights. Three of these flights co-manifest pressurized and unpressurized cargo, and one manifests pressurized cargo with the propulsion modules. At 51.6 degrees, seven to eight flights per year are required to supply logistics, assuming the use of the aluminum lithium external tank. The 12-rack mini-pressurized logistics module is carried five times (co-manifested with unpressurized cargo on two flights), every two years a replacement Bus-1 (or propulsion modules every year in Option A-2) flies on the sixth flight, and unpressurized cargo flies on the seventh and eighth flights. Space Shuttles with only advanced solid rocket motors reduce the logistics flights per year to the Space Station to six to seven flights. Using both the advanced solid rocket motor and the aluminum lithium external tank reduces the logistics flights to five per year.

Maintenance and Spares

The Option A plan and approach for maintenance is the same as that for Space Station Freedom. However, the amount of external maintenance is reduced by approximately 25 percent for A-1 and nine percent for A-2. The maintenance backlog during assembly is reduced by approximately 90 percent for A-1 and 70 percent for A-2, and is attributed to the insertion of several utilization flights between assembly flights and performing external maintenance activities on these flights. The steady state maintenance reduction is a result of hardware deletions and system simplifications from the Space Station Freedom (over 600 items deleted). The maintenance concept relies on robotics to perform nearly half the external maintenance. The remaining maintenance is accomplished using extravehicular activity. Although the extravehicular activity dual-rail cart and the mobile transporter are deleted, each is replaced with viable alternatives: the monorail cart and the robotics "inch-worm" mobility approach. Although the inch-worm approach slows down the transport of the robotics, the increased time is offset by utilizing ground control for some robotic activities.

Internal maintenance requirements for Option A were compared to similar results for the Space Station Freedom design. For Option A, the total number of replaceable items is reduced by about 25 percent. This results in a 40 percent reduction in internal maintenance crew-hours per year compared to Space Station Freedom.

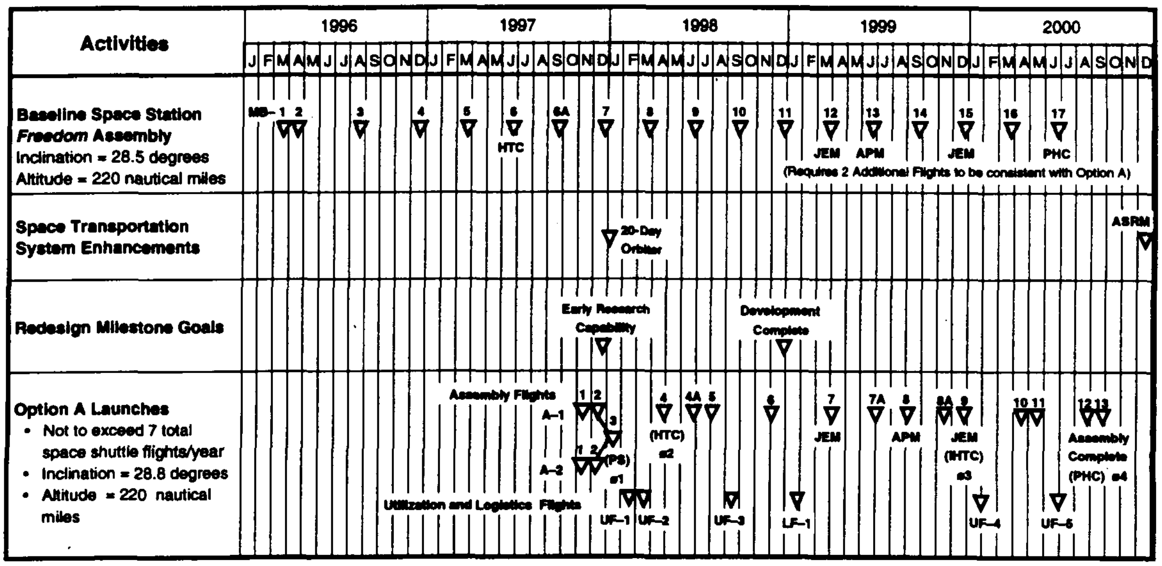
Schedule

The Option A assembly schedule is shown in Figure 41. First element launch is October 1997 and early research capability is achieved at the Power Station in late 1997. The goal of completing development by the end of 1998 utilizing fiscal year 1994 to 1998 funds is achieved, although actual orbital development continues in 1999 to 2000.

A top-level summary schedule for Option A-1 is depicted in Figure 42. This schedule includes design, manufacturing, assembly, test and delivery to Kennedy Space Center about six months prior to launch. Kennedy Space Center verification testing and launch processing are discussed in the Test and Verification section of this report.

Program plans call for the full implementation of hardware design updates beginning in October 1993, following concept selection. A requirements baseline review will be conducted about two months after contract authority to proceed. In the spring of 1994, a design update review is planned to review modifications to current Space Station Freedom program hardware that has already undergone a critical design review. Requirements and designs will be frozen at the completion of this review. A separate program design review and critical design review will be conducted for the common habitation module and other elements which have not been through the design review process (i.e., hardware on assembly flights 11 and 12).

For hardware common to the current program, the Space Station Freedom network logic



APM	Attached Pressurized Module
ASRM	Advanced Solid Rocket Motor
HTC	Human Tended Capability
IHTC	International Human Tended Capability
JEM	Japanese Experiment Module
MB	Mission Build
PHC	Permanent Human Capability
PS	Power Station (Early Research)

Assembly Flight Manifest

1. Bus–1 (Option A–1) or Photovoltaic Module (S4/S3) (Option A–2)
2. Photovoltaic Module (S4) (Option A–1) or two Prop Modules and Space Station Remote Manipulator System (Option A–2)
3. Radiators (S1) (20 kW)
4. Common Core/Lab

4A. Mini-Pressurized Logistics Module with Lab Outfitting Racks and Space Station Remote Manipulator System (Option A–1) or Mini-Pressurized Logistics Module with Lab Outfitting Racks (Option A–2)

5. Radiators (P1) and Special Purpose Dexterous Manipulator
6. Photovoltaic Module (P4) (40 kW)
7. Japanese Experiment Module

7A. Mini-Pressurized Logistics Module with Japanese Experiment Module System and Outfitting Racks & 1 Set of Cryo Bottles

8. Attached Pressurized Module (Moved to 9/99 at European Space Agency's Request)

8A. Mini-Pressurized Logistics Module with Outfitting and User Racks

9. Japanese Experiment Module Exposed Facility, Experiment Logistics Module Pressurized Section, Experiment Logistics Module Exposed Section
10. Photovoltaic Module (S6) (60 kW)
11. Common Module/Hab
12. Airlock and Closet Module with Hab Outfitting Racks
13. Two Assured Crew Return Vehicles

Utilization, Logistics, and Outfitting Flight Manifest

UF–1	Spacelab
UF–2	Spacelab Pallet and Cryo
UF–3	Mini-Pressurized Logistics Module with User Racks
LF–1	Bus–2 and Cupola (Option A–1) or Propulsion Module, Cupola, and Truss S–5 (Option A–2)
UF–4	Mini-Pressurized Logistics Module with Outfitting and User Racks and Cryo
UF–5	Mini-Pressurized Logistics Module with Hab User Racks

Note: First element launch is in 10/97, however a first element launch as early as 4/97 could be supported.

Figure 41
Option A launch schedule, with standard external tank

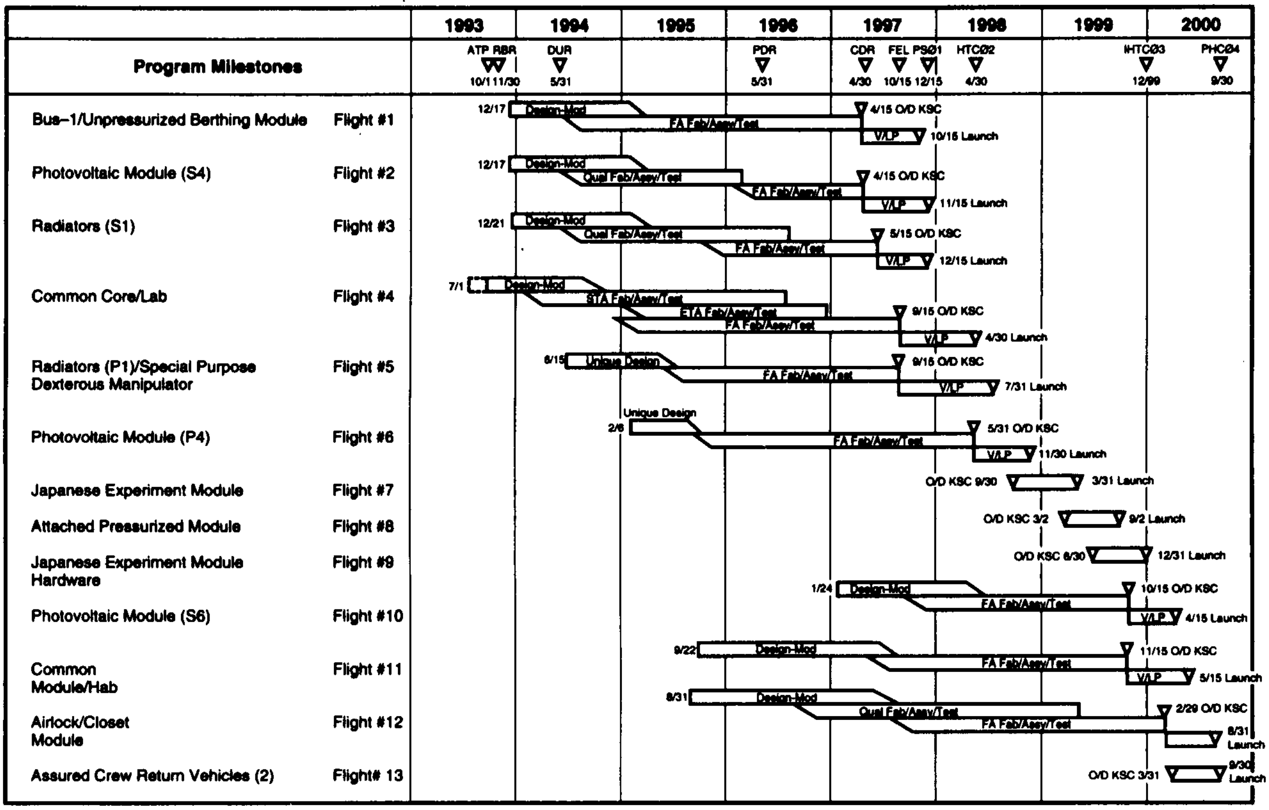
relationships and time estimating relationships have been largely adopted in developing the schedules. A time span for redesign of modified Space Station Freedom hardware has been included, as appropriate.

Space Station Freedom Requirements Not Incorporated

The requirements imposed on the redesign activity consist of those imposed by the Station Redesign Team guidelines. Program Requirements Document and the Program Definition and Requirements Document on the baseline Space Station Freedom were to be considered. However, these were challenged to reduce complexity and cost, while assuring sufficient margins against risk. Option A meets all safety requirements and meets most others within the constraints of the predominant factor—cost—and more closely satisfies some requirements than does Space Station Freedom.

Areas where Option A does not meet the Space Station Freedom requirements are:

- The Space Station Remote Manipulator System meets the schedule requirement for launch prior to Human Tended Capability in Option A-2, but is not launched until the next flight after Human Tended Capability in Option A-1.
- Nine International Standard Payload Rack locations are provided in the common core-laboratory module at Human Tended Capability instead of 13.
- Whereas the probability of no micrometeoroid or orbital debris penetration for Option A exceeds that of Space Station



ACRV	Assured Crew Return Vehicle	FEL	First Element Launch
APM	Attached Pressurized Module	JEM	Japanese Experiment Module
ATP	Authority to Proceed	JEM H/W	Japanese Experiment Module Hardware
RBR	Requirements Baseline Review	PDR	Program Design Review
CDR	Critical Design Review	PV	Photovoltaic
DUR	Design Update Review	SPDM	Special Purpose Dexterous Manipulator

Figure 42
Option A-1 schedule

Freedom, it does not completely meet the required probability of no penetration of 0.9955 per critical element.

- The fiber distributed data interface has been replaced with the 1553B data bus and the addition of a high-rate multiplexer and a remotely reconfigurable optical switching system.
- The mobile transporter has been deleted, but the function is provided by alternate means.

The Station Redesign Team requirements included some capabilities that were not in Space Station Freedom, and cannot be met by Option A without significant cost impacts. The new requirements for video compression of at least six channels and uplink video of one channel with medium fidelity are not met by Option A. Other areas where Station Redesign Team requirements are met with qualification are:

- Optical viewing requirements are met using an eight-inch optical quality window instead of the 20-inch window.
- Option A meets the normoxic condition requirements as stated in the engineering design guidelines of the Station Redesign Team requirements, but the more stringent carbon dioxide requirements in the Science, Technology, and Engineering Research Design Guidelines will require additional payload power (600 watts).
- Early or late access to the Space Station is provided at the launch or landing sites, and is provided via orbiter middeck utilization.
- Fire protection is single-failure tolerant.
- Manual override requires data management system interaction in most cases.

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Option B

Introduction

Option B uses mature Space Station Freedom designs and operations scenarios to provide an incrementally increasing capability throughout the assembly phase. Various stages of the assembly phase permit useful science as the configuration evolves. The first such stage, Power Station, comes after two Space Shuttle flights and provides power to a Spacelab-equipped orbiter for extended mission duration and experiment operations. The next stage, Human Tended Capability, is achieved in eight flights and provides the United States laboratory with sufficient resources to support tended and untended science for indefinite periods, with periodic resupply and maintenance using extravehicular activity and the Canadian robotic system. International Human Tended Capability is achieved after 17 flights and incorporates the Japanese and European laboratories with user power and thermal rejection capability exceeding 30 kW. Finally, the Permanent Human Capability is achieved after 20 flights and supports a crew of four, significantly increasing the amount and quality of science performed on the station. With the addition of modular elements, the Permanent Human Capability configuration can accommodate the full eight crew member and 75 kW power capability as established in the International Partner agreements.

Option B requires some changes to Space Station Freedom's assembly sequence, systems and elements. For example, a truss segment is deleted and modifications to the data management system separate internal and external functions, resulting in a more robust architecture for station survival and greatly simplified verification. In addition, the communications and tracking system data transfer format is changed to one equivalent to that used by the Space Shuttle program, allowing existing ground facilities and data processing architectures to serve both programs.

The Option B concept is compatible with the capabilities of the Space Shuttle without any further modifications than those now planned to support Space Station Freedom. Option B was designed for a 28.8 degree inclination orbit. However, it could also operate at inclinations up to 51.6 degrees but would require the aluminum lithium external tank. In addition, modifications to support automated docking capabilities would allow the use of expendable launch vehicles for cargo resupply.

Option B complies with the requirements and resource provisions of the Intergovernmental Agreement and Memoranda of Understanding with our International Partners and meets all NASA commitments with the International Partners. Also, use of the Russian Soyuz vehicle for assured crew return expands international involvement in the program.

Option Specific Requirements, Guidelines and Constraints

Several requirements drive Option B configuration and assembly: the orbit inclination, accommodation of International Partner elements, an assured crew return vehicle capability, the Space Shuttle as the launch vehicle and a permanent human presence in space. In accordance with design guidelines, the design must provide 30 kW to users at Permanent Human Capability attached payload ports, standard payload interfaces. It must support life science and microgravity research, and it must accommodate a 1.8 meter diameter centrifuge. The design must support a three or four person crew for 10 years and provide two-fault tolerance for crew and station survival.

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C-2

Description of Concept

External Configuration

Power Station

The first two assembly flights establish the Power Station by providing a fully functional spacecraft with one photovoltaic system with active thermal control, S-band communications, propulsion and control moment gyros for attitude control. Figure 43 illustrates the Power Station configuration. The Power Station provides one external payload port and dual, 6.25 kW power feeds to the orbiter for running experiments. The Power Station configuration provides single failure tolerance for Space Station survival. The four control moment gyros can control the combined orbiter and Space Station configuration to yield a better microgravity environment than available with orbiter thruster control alone. Option B Power Station matches the Space Station Freedom baseline flight 2 configuration except for minor modifications to the unpressurized berthing adapter to accommodate the Spacelab tunnel and power transfer.

Human Tended Capability

Flight 8 establishes the Human Tended Capability configuration, illustrated in Figure 44. It provides user capabilities in the United States laboratory module and to the two external payload accommodation locations. Performance characteristics include meeting the requirements of less than two microgravity for the 13 International Standard Payload Rack locations, a minimum of 8.5 kW power to the payloads, 72 kbps uplink, 50 Mbps downlink, and three nonstandard payload rack locations. The

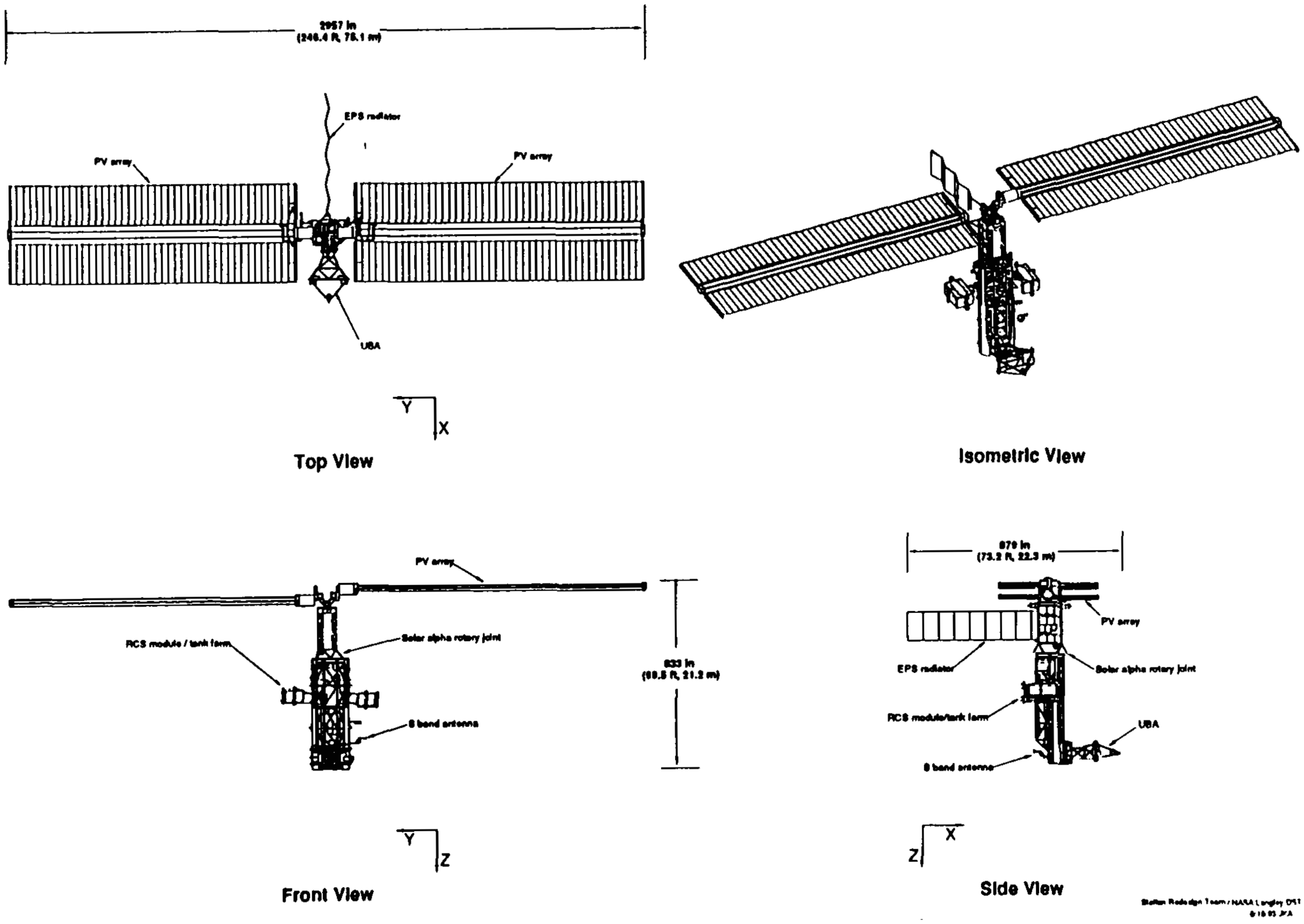


Figure 43
General arrangement - Power Station configuration

Human Tended Capability configuration can support payload operations both with and without the orbiter attached. This configuration also allows the docking of two orbiters simultaneously, which can extend crew duration on-orbit.

Option B can sustain the Human Tended Capability configuration indefinitely with periodic Space Shuttle flights for consumables and maintenance spares. The Canadian Space Station Remote Manipulator System and the Special Purpose Dexterous Manipulator provide robotics capability for Space Station maintenance. The Space Station-based airlock allows the orbiter crew to control the mobile servicing center from within the Space Station, while simultaneously performing extravehicular activity.

The Human Tended Capability configuration also includes the central thermal control system, which provides cooling for the pressurized elements (United States laboratory, node 2 and airlock), as well as externally mounted power conditioning equipment (DC to DC converter unit and main bus switching units). The gas conditioning assemblies and cryogenic berthing mechanisms provide the ability to replenish nitrogen and oxygen in the pressurized elements. The environmental control and life support system within the laboratory provides life support for the crew while the orbiter is attached. Provisions for attaching the mini-payload logistics module for pressurized logistics and the Japanese Experiment Module pressurized laboratory are included with node 2.

International Human Tended Capability

Flight 17 establishes International Human Tended Capability by adding the port side truss and the International Partner pressurized modules (Figure 45). This configuration has two-fault tolerance for Space Station survival, full power generation and thermal rejection capability and

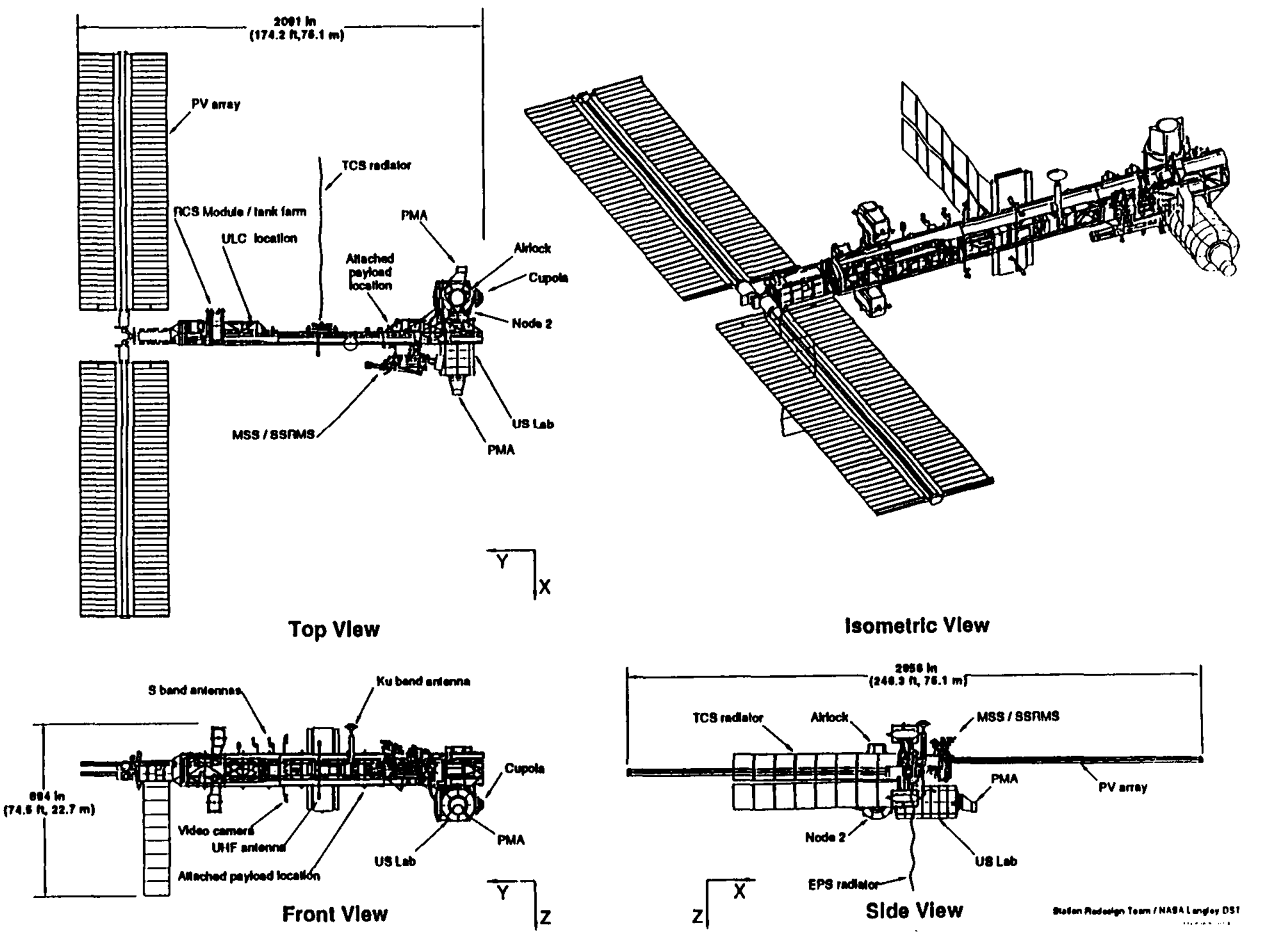


Figure 44
General arrangement - Human Tended Capability configuration

greater than 30 kW for payloads. International Human Tended Capability includes the full complement of United States and International Partner laboratories and elements: the Columbus Attached Pressurized Module, the Japanese Experiment Module and the Japanese Exposed Facility. The international laboratories all have less than one microgravity residual accelerations. The International Human Tended Capability configuration supports crew science operations during orbiter visits and untended science between Space Shuttle missions. The port side of the truss includes the second external active thermal control radiator, solar array, propulsion modules and a second alpha joint with two sets of solar arrays. The port propulsion modules provide reboost capability in a local vertical-local horizontal attitude. The configuration maintains two docking ports, the primary port on the front of the United States laboratory module and the backup port on the bottom of node 1. Option B deletes the P2 truss segment, shortens the truss and moves the unpressurized logistics carrier attach site to the S2 truss segment. The third set of solar arrays move to the port side of the truss, instead of the starboard side as in the Space Station Freedom baseline, placing the center of mass closer to the module pattern center and improving the microgravity environment. Option B can sustain this configuration indefinitely with periodic logistics flights for resupply of consumables and maintenance, including robotic and extravehicular activity maintenance for external equipment replacement.

Permanent Human Capability

Flights 18 through 20 add the United States habitation module and assured crew return vehicles to establish Permanent Human Capability (Figure 46). The additional hardware allows a permanent crew of four. The habitation module attaches to node 1, parallel to the United States

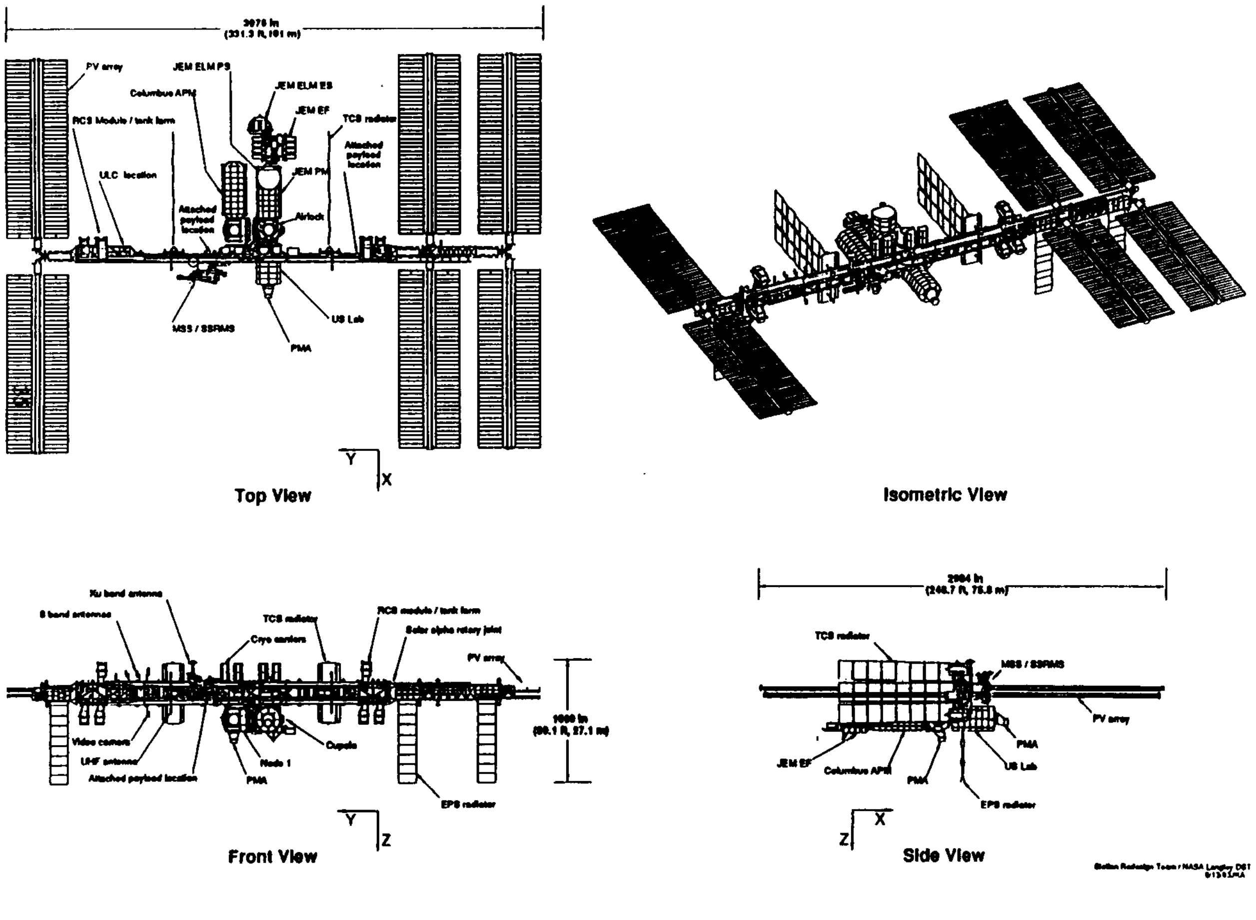


Figure 45
General arrangement - International Human Tended Capability configuration

laboratory. The Soyuz, which serves as the assured crew return vehicle, occupies the bottom port of node 1 that the Space Station Freedom baseline reserved for the pressurized logistics module. Consequently, Option B requires a new, temporary "swap" location for the payload logistics module on the truss or mobile servicing system. The Permanent Human Capability configuration has two docking ports: one is on the front of the United States laboratory, the other is on the front of the habitation module. The assembly sequence uses standard Space Shuttle upmass capabilities to 28.8 degrees (37,800 pounds to 220 nautical miles) and does not require the aluminum lithium external tank or the advanced solid rocket motors.

Alternative Configurations

The Option B team investigated three design alternatives: a Power Station capability as a stopping point, a Human Tended Capability as a stopping point and variations in the overall baseline configuration. By eliminating the need to grow, system complexity and size, and thus cost, can be reduced. The Power Station Capability and Human Tended Capability without growth assume no aluminum lithium external tank, advanced solid rocket motor or dual orbiter visits. These options must survive for two years without an orbiter visit. Also, variations in overall configuration showed promise but did not reduce overall costs.

Power Station Capability as a Stopping Point : This configuration consists of only the S4, S3 and S2 truss segments stripped of all hardware that do not directly support an orbiter with a Spacelab module (Figure 47). One center could manage this option with existing facilities, eliminating facilities such as: the Central Avionics Facility, Central Software Facility, Space Station Processing Facility, Space Station

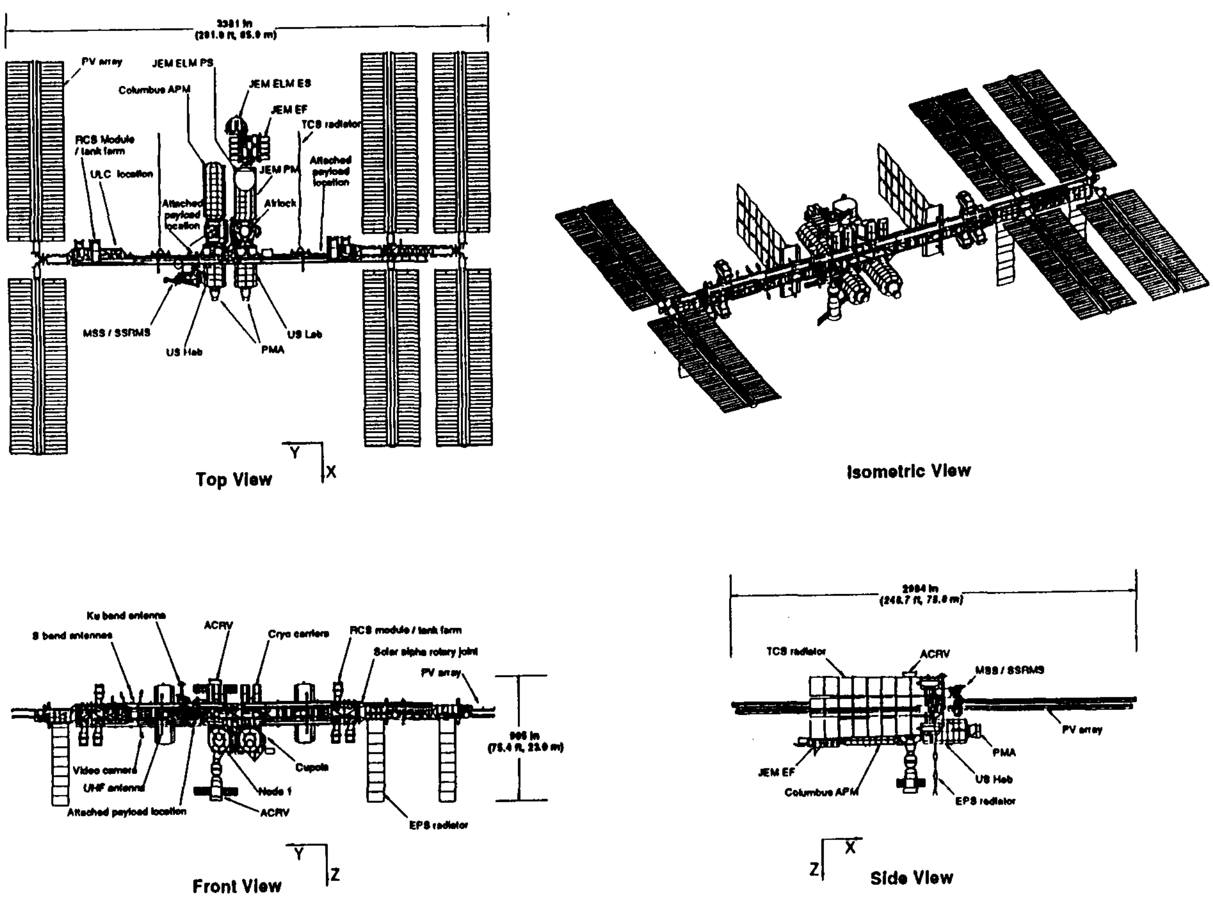


Figure 46
General arrangement - Permanent Human Capability configuration

Control Center and the Payload Operations Integration Center. This option deletes the mobile transporter and requires changes to the unpressurized berthing adapter to accommodate a Spacelab tunnel and transfer power from the station. The Power Station does not offer much greater capability than existing Spacelab flights.

The electrical power system would consist of the Space Station Freedom baseline photovoltaic module with a full battery complement. Power Station provides up to 9.0 kW additional power to an orbiter with a Spacelab module assuming full Sun tracking arrays. This leaves 4.0 kW of station power available for truss-mounted payloads (up to 1.5 kW), and Spacelab payloads up to 2.1 kW, concurrently, if orbiter thermal augmentation is used.

This Power Station configuration feeds power directly off the direct current switching unit to the orbiter via the unpressurized berthing adapter, as currently used for Space Station activation on flight 2. The electrical power system deletes all four DC to DC converter units on the S2 segment, leaving only the DC to DC converter units outboard of the alpha joint for core loads.

The thermal control system consists of the photovoltaic active thermal control system, the passive thermal control system and the orbiter. The photovoltaic active thermal control system and the passive thermal control system strongly resemble those of stage 2. The thermal control system passively cools all avionics, deleting four DC to DC converter unit cold-plates, ammonia lines and associated valves and sensors. Orbiter radiators reject the total of 21.9 kW waste heat resulting from a combination of station supplied power, orbiter fuel cell power and crew metabolic loads. The orbiter can radiate a maximum of 23.9 kW. However, deploying the forward radiators can increase this amount by up to 10 percent. Using the orbiter flash evaporator system, this Power Station configuration can reject an additional 30.1 kW-hour per day at a peak rate of 9.6 kW.

The Power Station as a stopping point configuration significantly simplifies the data management system architecture by utilizing the orbiter attitude control hardware and existing prototypes. The communication and tracking sys-

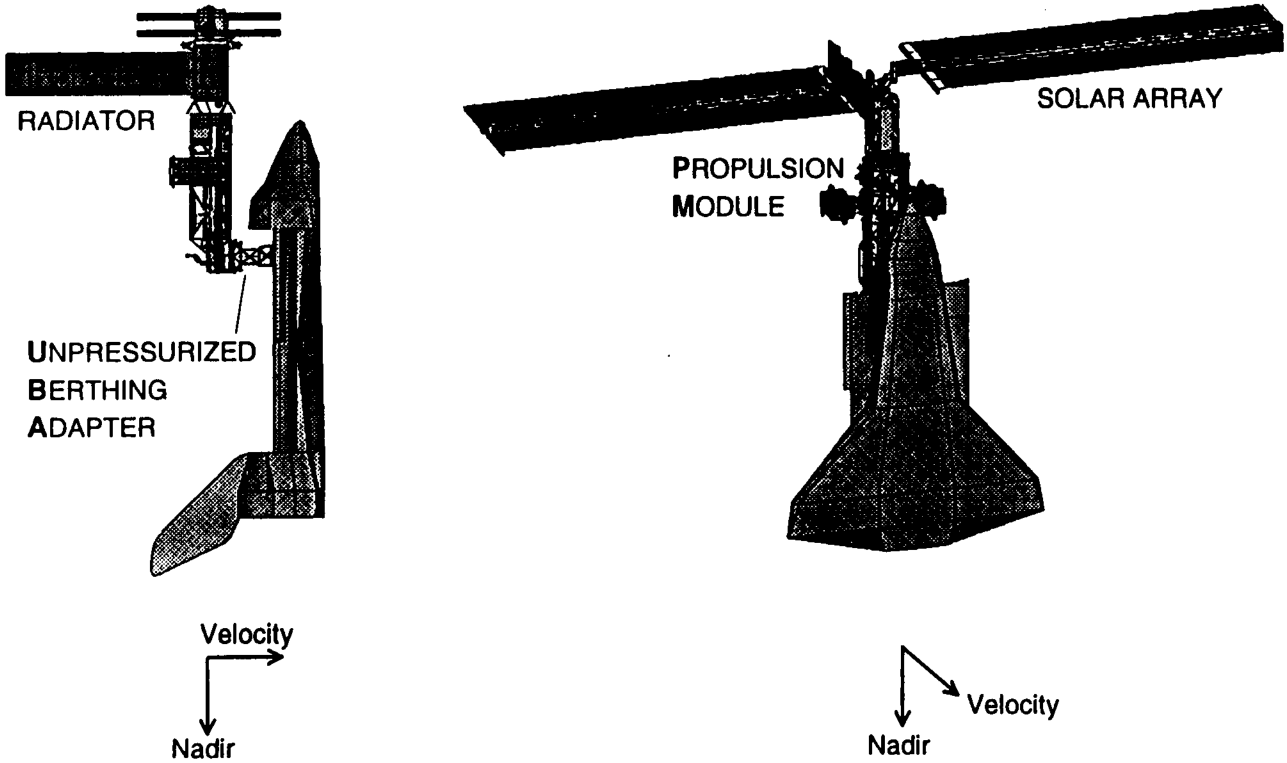


Figure 47
Option B Power Station-no growth configuration

tem remains unchanged but may utilize commercial S-band equipment.

In this option, two control moment gyros are deleted from the guidance, navigation and control. This option requires two propulsion modules for reboost and collision avoidance.

Human Tended Capability as a Stopping Point : This option provides an on-orbit pressurized laboratory module tended by an orbiter and its crew. The configuration provides up to 8.5 kW of power to the laboratory experiments. This option requires redesign of the thermal control system and the structure attaching the module to the truss. Flight number eight was chosen as a sustainable Human Tended Capability stopping point to accommodate onboard extravehicular activity capability. This is different from the Space Station Freedom program which declares Human Tended Capability before the airlock is available.

The configuration, as illustrated in Figure 48, has several significant differences with the Option B Human Tended Capability. The configuration requires five assembly flights by deleting the M1 truss segment and the node. The five assembly flights do include a mini-payload logistics module with 5200 pounds of payload. The configuration includes the Canadian Space Agency elements, the Space Station Robotic Manipulator System and Special Purpose Dexterous Manipulator, but does not accommodate the Japanese Experiment Module or the Columbus Attached Pressurized Module. The United States laboratory mounts directly under the S1 truss segment, and thus requires support

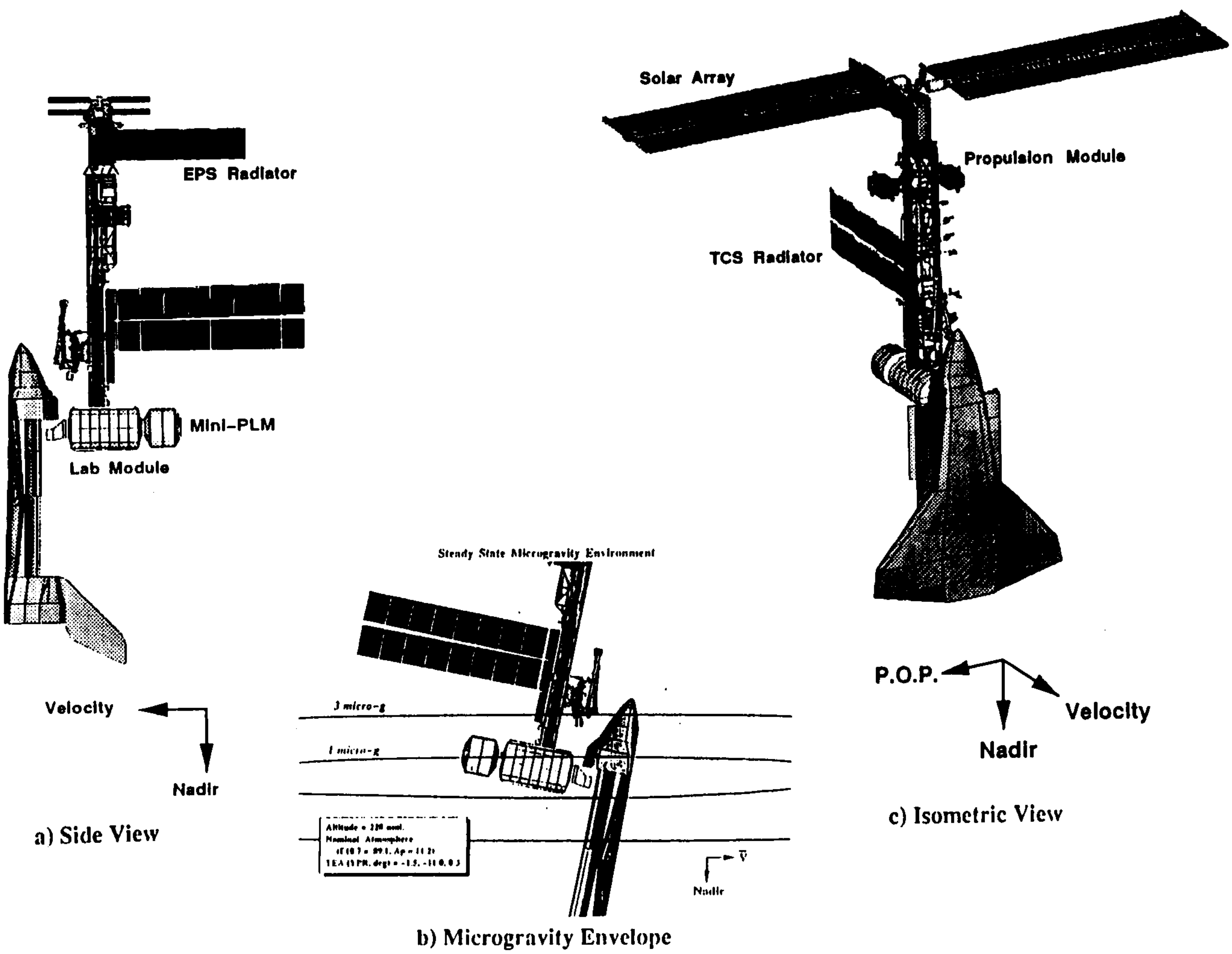


Figure 48
Option B Human Tended Capability-no growth configuration

structure modifications. The United States laboratory has a single orbiter docking port in the front and a mini-payload logistics module port in the rear. Over 70 percent of the United States laboratory volume lies within the one microgravity environment with an attached orbiter. This configuration uses an orbiter aft flight deck workstation instead of a station based robotic workstation. The main bus switching units on the M1 truss segment would move to the S1 section. High pressure gaseous oxygen and nitrogen tanks on S1 replace the cryogenic gas conditioning assemblies on M1.

With the exception of the thermal control system, the systems remain relatively unchanged from the Option B Human Tended Capability configuration. The intermediate rate gateway is deleted from the data management system. In the communication and tracking, the ultra high frequency capability is deleted, the orbiter based wireless audio subsystem and the number of video switches and camcorders is reduced. The guidance, navigation and control system remains unchanged. Two Space Station Freedom baseline hydrazine propulsion modules are on the configuration for reboost and collision avoidance capability. Two of the four main bus switching units scheduled for installation on truss segment M1 are deleted from the electrical power system. The two phase external active system with a single phase system is replaced with a single phase system in the thermal control system. This system uses photovoltaic active thermal control system components and includes two single phase radiator orbital replacement units mounted on a rotary joint to give continuous heat rejection of at least 23.3 kW in addition to heat load rejected passively. The available power capability remains unchanged.

Configuration Variations: Space Station Freedom baseline components can be assembled and arranged in different ways to achieve various levels of performance and flexibility. The team considered several variations of the nominal configuration, but ultimately rejected them due to unacceptable cost versus benefit.

The team rejected deleting the starboard thermal section (S1) because it could not grow to meet desired power and thermal objectives.

Deleting the whole port truss would eliminate two segments and an alpha joint. Two solar power modules would appear on the starboard side of the truss thus producing an asymmetric configuration. The configuration would have a single alpha joint and a single thermal segment (S1). The team rejected this idea due to redundancy concerns, thermal limitations, early intra-array shadowing, large control requirements, large yaw flight attitudes and a poor microgravity environment.

Combining the thermal segments (S1, P1) and the M1 segment into two smaller truss segments reduces the number of flights to Human Tended Capability, with a reduced thermal rejection capability. The cost of redesign for this configuration led to its removal from consideration early in the configuration selection process.

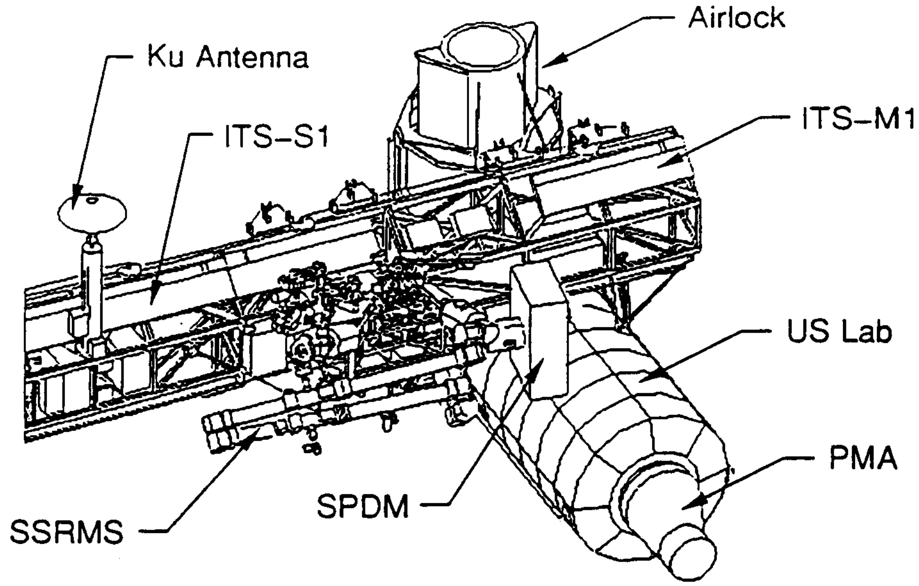
Distributing habitation functions among all the pressurized elements could eliminate the habitation module. This would save the cost of the shell but not the system hardware. This also would reduce payload volume in all three laboratories. A separate habitation module proved worth the marginal increase in cost as opposed to distributing the habitation functions throughout the remaining pressurized modules.

To accommodate dual, simultaneous orbiter docking at the station, the Columbus Attached Pressurized Module was rotated toward zenith with a pressurized mating adapter at one end. The modifications to the Columbus Attached Pressurized Module, along with a poor microgravity environment and serious doubts about the viability of dual orbiter operations, resulted in a return to the original module pattern and the elimination of the dual simultaneous orbiter requirement.

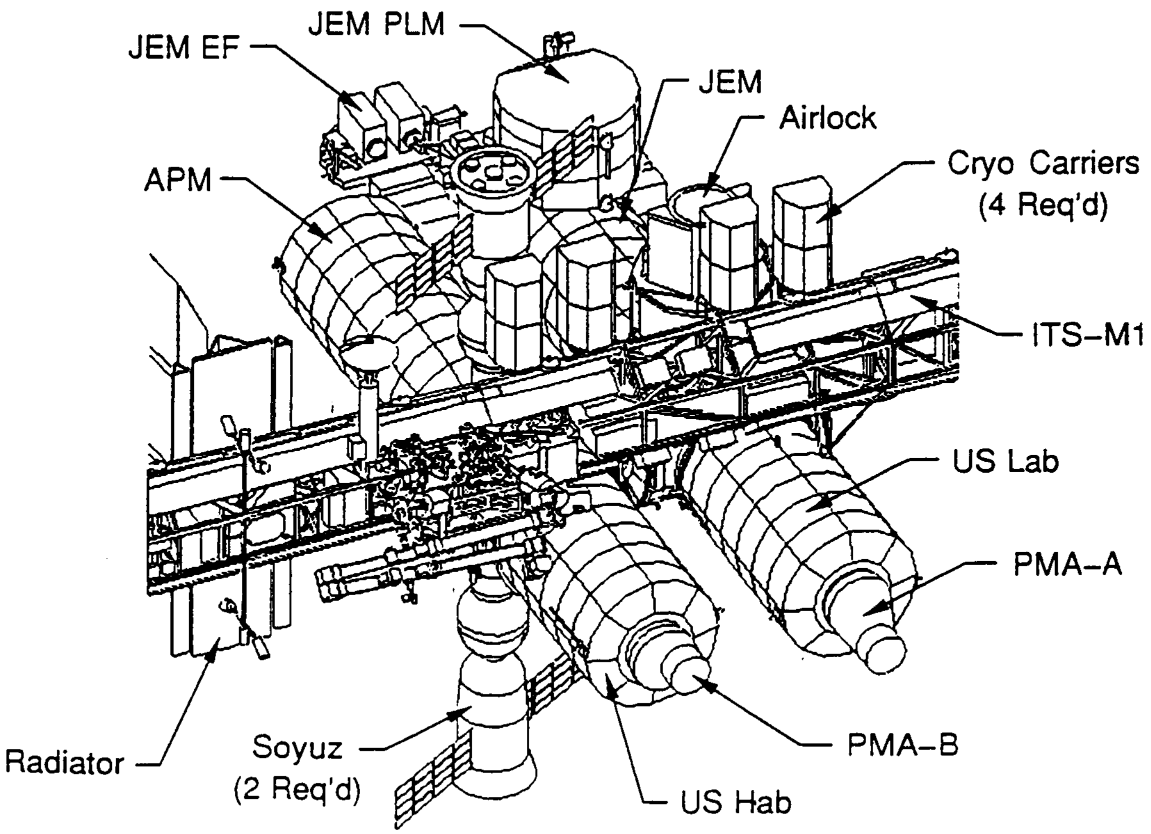
Internal Configuration

The pressurized modules contain equipment to provide laboratory, habitation, logistics resupply and overall station command and control functions. Figure 49 illustrates the module pattern at Permanent Human Capability. The modules are cylinders capped with end cones and berthing mechanisms. Four interior horizontal standoffs, oriented 90 degrees apart, run the length of the module for routing utilities through the module and to the berthing ports.

Racks, standoffs and end cones contain all the active equipment in the modules. Figure 50 shows the internal layout of the pressurized modules. System racks contain equipment for electrical power, data management, thermal con-



Human Tended Capability



Permanent Human Capability

Figure 49
Option B module pattern

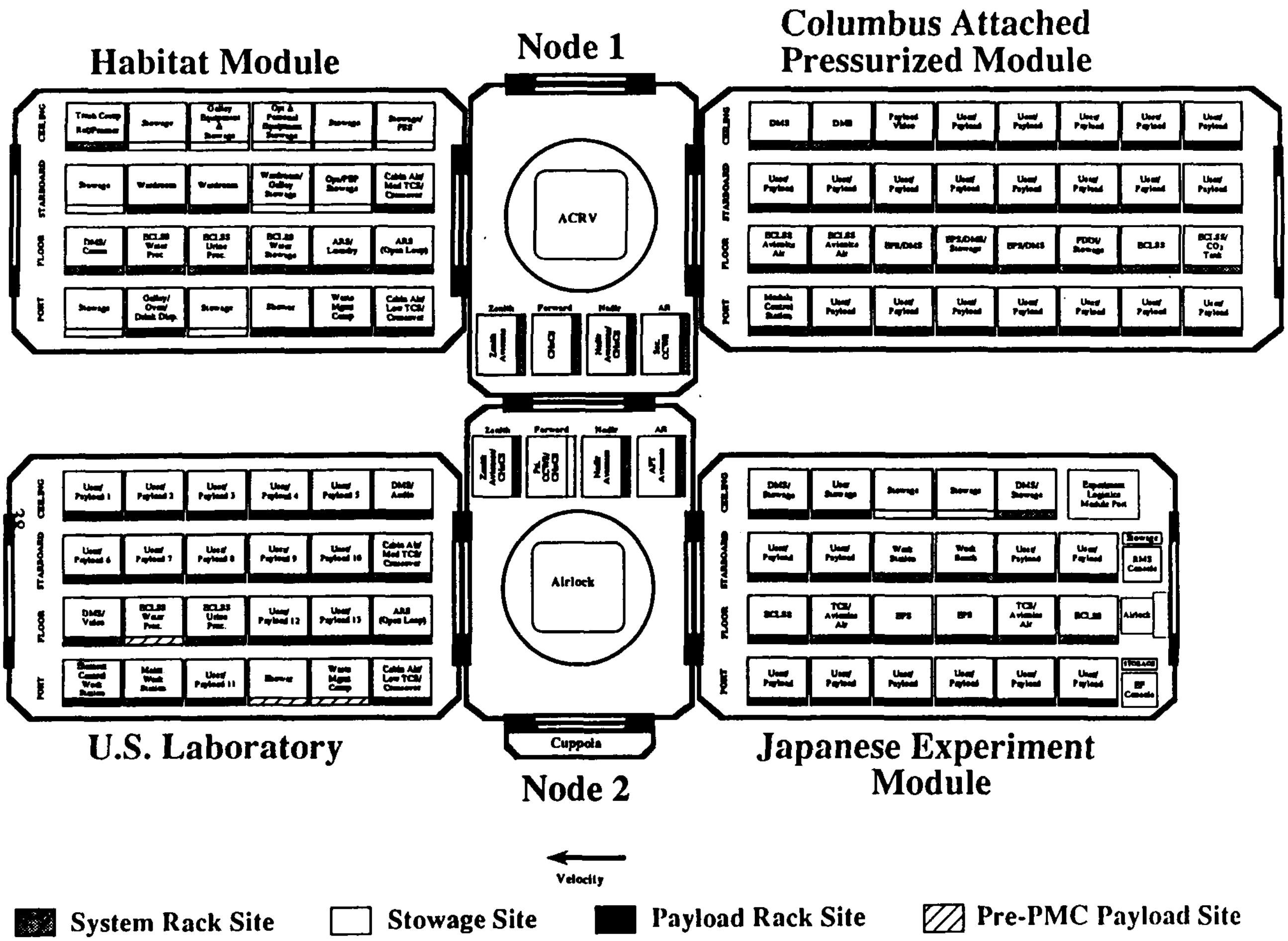


Figure 50
Internal rack layouts at Permanent Human Capability

trol, audio and video, life support and crew systems. International Standard Payload Racks contain unique payload equipment provided by station users.

The resource nodes provide the primary structural interconnect for other pressurized habitable elements and for the passage of personnel, equipment and utilities. Each node provides four radial and two axial berthing ports. The cylindrical section accommodates four system racks. Node 2 is launched on flight 5 and contains crew health care system equipment, three avionics racks and the primary command and control work station. Node 1 on flight 12 contains avionics and crew health racks and secondary command and control.

Flight 6 delivers the 24-rack laboratory module providing a shirt sleeve environment for conducting microgravity research. At Human Tended Capability, the laboratory will have eight system racks installed, 13 International Standard Payload Rack positions and three temporary, nonstandard payload rack positions. At Permanent Human Capability, the three nonstandard payload racks convert to system racks. The habitation module provides general living space for a crew of four and is launched on flight 18. It will accommodate a total of 24 racks—10 system racks, 10 stowage racks and four functional units. The mini-pressurized logistics module provides for the delivery of experiment racks and logistics resupply during the assembly sequence. It accommodates the equivalent of eight racks—one system rack and seven stowage racks.

The international modules include the Japanese Experiment Module and Columbus Attached Pressurized Module. The Japanese Experiment Module is launched on flight 13 and will have a total of 23 racks: 10 system racks,

Table 20
Option B assembly manifest to 51.6 degree inclination

Date	Milestone	Flight #		Elements
10/97	FEL	1	MB-1	ITS-S4, ITS-S3, STBD INBD SOLAR ARRAYS (2), MT
11/97		2	MB-2	ITS-S2, UBA, CETA (1)
12/97	PS	3	MB-2A	PMs (2)
3/98		4	MB-3	ITS-S1, STBD TCS (minus 1 TCS ORU), TDRSS Antenna, SSRMS
5/98		5	MB-4	ITS-M1, GCAs (2), NODE 2 UMB, LAB UMB, PWP (2)
7/98		6	MB-5	NODE 2, PMA-A
8/98		7	MB-6	U.S. LAB (minus ECWS, WATER STOW. RACKS)
9/98		8	MB-6A	MPLM-A (MWS, 6,000# P/L, ECWS, WATER STOW. RACKS), MBS, PMA-B
12/98		9	MB-7	ULC, CNC, COC, PV#1 BATTS, CETA (1), SPDM/MMD
3/99	HTC	10	MB-7A	AIRLOCK, EMUs (3), PFRs (2), CUPOLA
6/99		11	MB-8	ITS-P1, PORT TCS
9/99		12	MB-10	ITS-P3, ITS-P4, PORT INBD SOLAR ARRAYS (2) (minus all batteries)
12/99	2 PVs	13	MB-10A	PV#2 BATTS, UMBs: NODE 1, JEM, APM, HAB
3/00	2 FT	14	MB-9	PMs (2)
6/00		15	MB-11	NODE 1, ITS-P5
9/00	(170 nmi)	16	MB-12	JEM MODULE (W/CORE SYSTEMS)
12/00		17	MB-12A	JEM OUTFITTING
3/01	(185 nmi)	18	MB-13	COLUMBUS APM (W/CORE SYTEMS)
6/01		19	MB-13A	APM OUTFITTING
9/01	3 PVs	20	MB-14	ITS-P6, PORT OTBD SOLAR ARRAYS (2)
12/01	IHTC	21	MB-15	JEM EF, JEM ES, JEM PS
3/02		22	MB-16	HAB MODULE
6/02		23	MB-16A	MPLMS WITH HAB OUTFITTING
9/02		24	Soyuz-1	ACRV-1
12/02	PHC	25	Soyuz-2	ACRV-2

Assumes: 51.6° inclination. AlLi External Tank (Available 10/97, 7.5 klbs., All Flights)
International Modules launched withcore systems utilizing 1800 pound SSF manages reserve and altitude strategy.

two stowage racks, 10 International Standard Payload Racks and one nonstandard position for users. The Columbus Attached Pressurized Module is launched on flight 14 and will have a total of 32 racks: 10 system racks, 20 International Standard Payload Racks, and one nonstandard position for users.

Mission Considerations

Orbital Inclination

A higher inclination allows multiple access using space transportation systems operated by several nations, including Russia, which may provide more operational flexibility for long-term logistical resupply. In general, the study concluded that placing Option B at the higher inclinations is feasible but carries large costs for Space Shuttle transportation and substantially lengthened the hardware development schedule.

The high inclination study assumed the same Option B configuration since no operational or research requirements were relieved at the high inclination. All flight manifesting studies assumed Space Shuttle lift performance capability to 51.6 degrees is reduced 12,800 pounds without other performance augmentations. As shown in Table 20, the assembly will require 25 flights for element delivery and on-orbit outfitting, an increase of five flights from the Option B reference sequence, because of the reduction of Space Shuttle performance. These flights require the aluminum lithium external tanks.

Advanced solid rocket motor availability in December 2000 allows its use late in the sequence. These additional flights, combined with the later first element launch start date, will delay Permanent Human Capability to March 2002. The additional assembly flights can be avoided by lowering the orbit inclination to 43 degrees and using the same assembly sequence as the Option B reference assuming the aluminum lithium external tanks for all flights.

Option B at 51.6 degrees delays activation, attitude control and reboost capability until the third flight. This will increase the sensitivity to delays in Space Shuttle flights and makes the passive damper design and integration much more critical. All rendezvous with passive stages will be much more sensitive to thrust perturbations and may increase the risk of rendezvous wave-offs.

The logistics requirements for Option B do not change at the higher inclination in terms of pounds of logistics per year but do demand more Space Shuttle flights to support them. The integrated logistics scenario is dependent upon the inherent flexibility to utilize different logistics carriers to minimize the total number of Space Shuttle flights required per year. Option B at 28.8 degrees requires five flights per year after Permanent Human Capability with the advanced solid rocket motors. At 51.6 degrees, Option B will require up to six flights per year with advanced solid rocket motors. This can be reduced to five flights per year with the additional performance augmentation of the aluminum lithium tank.

Higher inclination has no appreciable affect on the external active thermal control system but carries adverse impacts on passively cooled components. The predicted temperatures for the standard data processors mounted on truss segment S2 exceed maximum operational temperatures and fall below minimum nonoperational limits at extreme beta angles of plus or minus 75 degrees. The effect of continuous 100 percent solar illumination for several days on truss electronics in extravehicular activity corridors and on module temperature requires further study. Also requiring further study are the effects of extended dormancy for truss mounted electronics and extreme beta angles on module external temperatures.

The higher inclination places the Space Station in more adverse micrometeoroid and orbital debris and ionizing radiation natural environments. While neither creates radically different design factors for Option B, the more severe environments must be appropriately considered in the design. This inclination forces reoptimized micrometeroid and orbital debris shielding to protect against the higher flux and more oblique incidence angle as compared to the Space Station Freedom baseline design environment. The higher ionizing radiation environment is likely to result in a higher incidence of avionics parts single event effects, which will require more data management system resources to carry out avionics resets. The radiation environment also may necessitate minor constraints on extravehicular activity and certain long-duration crew assignments to avoid exceeding annual crew exposure limits.

Orbital Environment

The Option B micrometeroid and orbital debris protection is identical to Space Station Freedom. Currently, a meteroid and orbital debris enhancement study for Space Station Freedom is nearing completion. It is expected that, when completed, the overall Space Station protection will be approximately 90 percent probability of no penetration during the projected 10-year lifetime. This may require approximately 2600 pounds weight increase to the laboratory and habitation modules. The cost has not been included in the weight summary and is carried as an issue.

Flight Modes and Propellant Utilization

The flight characteristics vary for each stage due to changing mass properties and solar array position. Table 21 summarizes the flight orientation and attitudes for each phase. The torque equilibrium attitude, control moment gyro requirements and orbital lifetime appear relatively insensitive to orbital inclination. The control moment gyros' momentum for all stages fall well below the maximum capacity, providing sufficient reserves for contingency and on-orbit operations.

Stage 1 flies in a gravity gradient flight orientation and uses five passive magnetic dampers for attitude control. The launch altitude of 220 nautical miles yields more than three times the minimum lifetime requirement of 180 days to 150 nautical miles (Figure 51). The solar arrays remain stowed on stage 1 with reboost 30-days later on stage 2. Flights 2 through 4 are maintained in a gravity gradient orientation with reboost in an arrow orientation. The solar arrays are deployed but remain locked and feathered. Control moment gyros provide primary attitude control with thrusters as backup. Subsequent assembly flights fly in local-vertical-local-horizontal orientation, with sun-tracking solar arrays. Starting at flight 10, reboost occurs in a local-vertical-local-horizontal orientation, taking advantage of the presence of the port propulsion modules.

Rendezvous Approach

The orbiter's rendezvous approach to the station varies throughout the early part of the assembly

Table 21
Option B flight characteristics summary

Flight	Attitude Mode	Rendezvous		Reboost Mode	Ballais. Coeff.	# of CMGs
		Mode	Alt (nmi)		Kg/M2	Passive
MB-1	GG, UD		193	169.1.8.0.89.5	94	<1
MB-2	GG,F	GG	190.7	0.1,-0.2,-95.0	89.8	<1
MB-3	GG, F	GG	220	1.2,-0.6,-91.0	91.3	<1
MB-4	GG, F	GG	220	0.2,0.1,-89.6	86.4	<2
MB-5	LVLH, S	GG	220	-9.7,1.4,7.2	42.9	<2
MB-6	LVLH, S	LVLH	21.83	-8.51.2,7.7	49.8	<2
HTC	LVLH, S	LVLH	220	-6.7,0.7,5.7	52.2	<2
I-HTC	LVLH, S	LVLH	TBD	7.0,13.9,0.5	53.8	<2
PHC	LVLH, S	LVLH	TBD	-8.5,-16.0,0.0	58.5	<2

UD: Undeployed arrays
F: Feathered and locked arrays
S: Sun tracking arrays

TEA and Ballistic coefficient calculations assume 2σ atmosphere on date of launch and an altitutde of max (220 nmi, 180 days to 150 nmi)

Steady state CMG control at 220 nmi, design atmosphere

process, but remains unchanged after the seventh assembly flight when the Shuttle uses a plus V-bar approach to the station in a local-vertical-local-horizontal attitude. On assembly flight 2, the station has no active attitude control to maneuver for orbiter approach and is in a unique torque equilibrium attitude with the solar arrays pointed toward Earth. The orbiter approach will occur near the minus R-bar in order to approach the minus Y face of the station, limiting orbiter plume effects on the passively stabilized stage and locating the grapple fixture in the proper relative position for capture by the station remote manipulator system. For flights 3, 4 and 5, the station will hold a gravity gradient attitude using attitude control system thrusters with the unpressurized berthing adapter biased off the V-bar to allow greater clearance for capture as the orbiter approaches down the positive V-bar. On flights 6 and 7 a rotational maneuver is required from the local-vertical-local-horizontal flight mode to the gravity gradient hold approach attitude.

Docking and Berthing: For all flights prior to the attachment of the first pressurized module, an unpressurized berthing adapter will be used to berth the station into the orbiter payload bay with attachment being provided by payload retention latches. The unpressurized berthing adapter will be located on the station near the port end of the completed stage and will allow a tail-to-Earth orbiter approach to the gravity gradient station. After the addition of node 2 and the pressurized mating adapter, the orbiter will gain pressurized access to the station using an external airlock configuration with an orbiter docking system mounted on top. The orbiter approach to the station will be tail down. A pressurized mating adapter on the aft port of node 2, will allow docking to a gravity gradient station for flights 6, 7, and 8. A second pressurized mating adapter on the forward port of the United States laboratory will permit docking to a local-vertical-local-horizontal aligned station for utilization flight 1 and subsequent flights.

Array Feathering Sequence: The timing of the solar array feathering and unfeathering during the rendezvous sequence relates to the feathered angles and power generating capability of the arrays while in their feathered position. The power requirements of the station at a given stage of assembly and the resulting depth of dis-

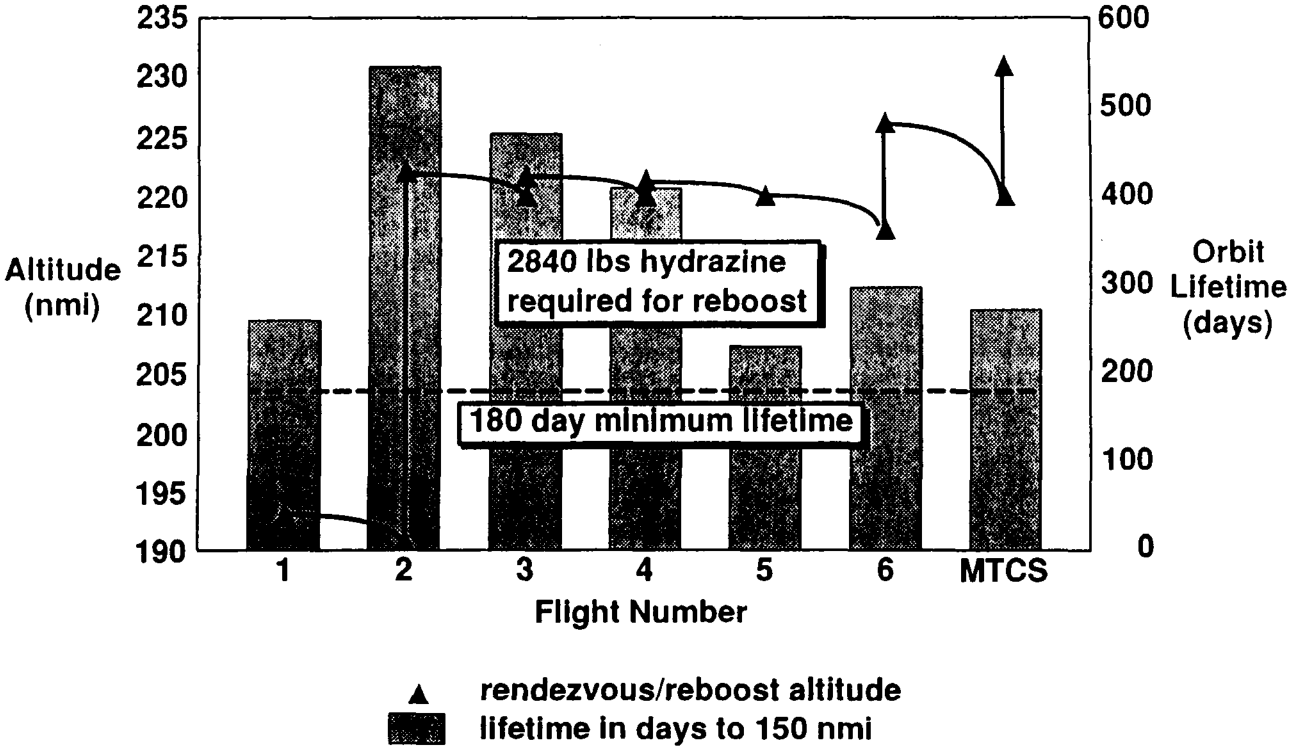


Figure 51
Orbit lifetime analysis for Option B

charge reached during the feathered sequence determine the appropriate timing of the feathering. For flights 3 through 5, the station has low power requirements and good feathering angles for power generation, so timing is not critical for feathering and unfeathering operations. After flight 5, however, relatively large station power requirements and potentially poor feathering angles for power generation causes the timing of the feathering and unfeathering of the arrays to become critical.

Assembly Scenario

Option B assembly concept builds on Space Station Freedom baseline scenarios to provide an incrementally increasing capability throughout the assembly phase. The assembly sequence incorporates four milestones or "stopping points:" Power Station, Human Tended Capability, International Human Tended Capability and Permanent Human Capability. Table 22 shows the detailed assembly manifest, including flight mass margins, total mass on-orbit, assembly extravehicular activity and stage functionality. Figure 52 illustrates the relationship between the Space Station Freedom baseline and Option B assembly sequence. Option B deletes the mobile transporter batteries and truss segment P2 from the Space Station Freedom baseline.

Each of the four milestones offers a logical stopping point. The Power Station configuration can provide for extended orbiter stay times; in these cases orbiter onboard stowage and crew physiology become the pacing items for on-orbit duration, rather than power and cryogen supply. The Human Tended Capability configuration incorporates the necessary equipment for sustained operations, including two-failure tolerance for station survival and station-based extravehicular activity and robotics. The International Human Tended Capability configuration combines the full International Partner laboratory complement with the power needed for simultaneous utilization of all three laboratories. Finally, the Permanent Human Capability configuration provides the necessary equipment to support a four-person crew independent of the orbiter, including an assured crew return capability.

The evolution of the Space Station configuration between Human Tended Capability and

Table 22
Option B completes assembly to Permanent Human Capability by December 2001

Date	Milestone	Flight #		Elements
Oct-97	FEL	1	MB-1	ITS-S4, ITS-S3, STBD INBD SOLAR ARRAYS (2), MT, UBA
Nov-97	PS	2	MB-2	ITS-S2, PMs (2)
Feb-98		3	MB-3	ITS-S1, STBD TCS, TDRSS ANTENNA, SSRMS
Apr-98		4	MB-4	ITS-M1, CETA, GCAs, Node 2 UMB., LAB UMB., PWP, Batteries
May-98		5	MB-5	NODE 2, PMA-A
Jun-98		6	MB-6	U.S. LAB (800# PAYLOAD RACKS), PMA-B (ON LAB)
Sep-98		7	MB-6A	MPLM-A (MWS, 5,200# PAYLOAD RACKS), SPDM/MMD, MBS
Dec-98	HTC	8	MB-7	AIRLOCK, EMUs (3), PFRs (2), CUPOLA
Mar-99		9	MB-8	ITS-P1, PORT TCS, UMBILICALS: NODE 1, JEM, APM, HAB
Jun-99	2 PVs	10	MB-10	ITS-P3, ITS-P4, PORT INBD SOLAR ARRAYS (2)
Sep-99	2 FT	11	MB-9	PMs (2), ULC, PV#2 BATTERIES
Dec-99		12	MB-11	NODE 1, ITS-P5
Mar-00		13	MB-12	JEM MODULE
Jun-00		14	MB-13	COLUMBUS APM
Sep-00		15	MB-13A	JEM & APM OUTFITTING
Dec-00	3 PVs	16	MB-14	ITS-P6, Port OTBD PV (2) (3 SETS of BATTERIES)
Mar-01	IHTC	17	MB-15	JEM EF, JEM ES, JEM PS
Jun-01		18	MB-16	HAB
Sep-01		19	MB-16A	HAB OUTFITTING
Dec-01	PHC	20	MB-17	ACRV-1, ACRV-2

a) Summary Assembly Manifest

Launch Date	Mile-stone	Flight Num.	Flight Name	Primary Cargo	Cargo Mass (lbs)	Mass Margin (lbs)	Total On-Orbit Mass (lbs) [1]	Assembly Altitude (nmi)	Assembly EVA Est. (man-hrs)	Assembly EVA Alloc. (man-hrs)	Stage Functionality
Oct-97	FEL	1	MB-1	PV 1	36689	77	36689	193	23	24	Passive S/C
Nov-97	PS	2	MB-2	S2, Prop	30458	583	67147	190	21	24	14.9 kW Payload, Power, Active S/C
Feb-98		3	MB-3	S1, TCS	31646	520	98793	220	21	24	STB TCS
Apr-98		4	MB-4	M1, GCA	31018	1249	129811	219	22	24	O2/N2 Supply,Active TCS
May-98		5	MB-5	Node 2	26572	1725	156383	217	24	36	Pressurized Volume
Jun-98		6	MB-6	US Lab	31054	26	187437	212	19	24	SSF IVA Ops
Sep-98		7	MB-6A	Lab Outfit	21139	5867	208576	220	13	24	Outfitted Lab
Dec-98	HTC	8	MB-7	Airlock	19679	8328	248255	215	16	24	Sustainable S/C
Mar-99		9	MB-8	P1, TCS	28968	2513	277223	210	16	24	Port TCS
Jun-99		10	MB-10	PV 2	32119	62	309342	203	23	24	46.9 kW, 2 FT Total Power
Sep-99		11	MB-9	Prop	28783	19	338125	214	0	12	2 FT S/C
Dec-99		12	MB-11	Node 1	23409	6193	361534	220	18	24	Redundant Node
Mar-00		13	MB-12	JEM PM	30172	0	391706	220	24	36	JEM Laboratory
Jun-00		14	MB-13	APM	30176	0	421882	220	18	36	ESA Laboratory
Sep-00		15	MB-13A	Int'l Outfit	16000	99	437882	220	0	0	Outfitted JEM & APM
Dec-00		16	MB-14	PV 3	27110	3371	464992	220	24	24	68.3 kW Total Power
Mar-01	IHTC	17	MB-15	JEM EF	28101	0	526986	220	12	12	JEM Exposed Facility
Jun-01		18	MB-16	Hab	30120	0	557106	220	17	24	Habitation Functions
Sep-01		19	MB-16A	Hab Outfit	16000	99	573106	220	0	0	Outfitted Hab
Dec-01	PHC	20	MB-17	ACRV 1	35060	-5575	608166	220	0	0	Permanently Manned

NOTES
[1] Includes mass of payload racks delivered on UF flights

b) Detailed Assembly Manifest

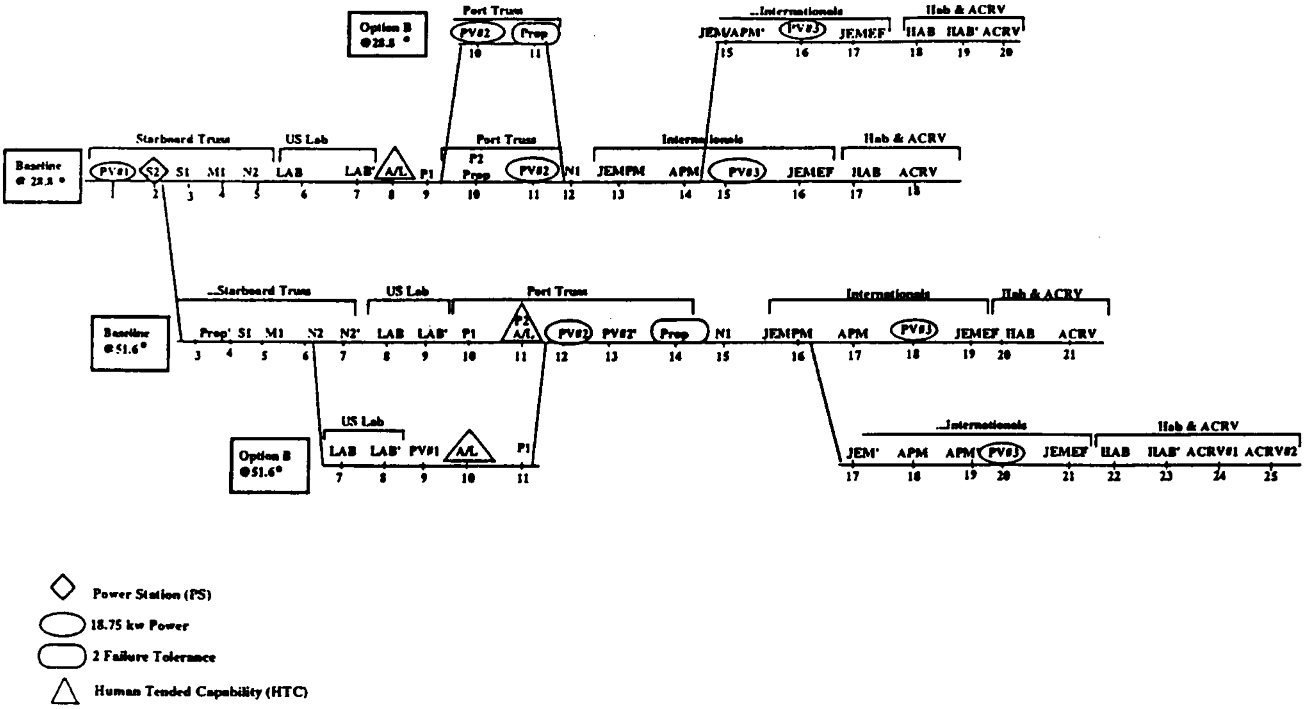


Figure 52
Option B vs. Space Station Freedom baseline assembly sequence, 28.8 degrees and 51.6 degrees

Permanent Human Capability is flexible. The current Option B assembly approach initially emphasizes high power for materials science in the human-tended phase,'then adds the capability for greatly extended crew stay times for life sciences in the Permanent Human Presence phase. If utilization emphasizes early life science, modifications to the post-Human Tended Capability assembly sequence, and resulting on-orbit configuration, could bring one or more International Partner laboratories, the habitation module or a centrifuge.

Systems Description

Option B is derived from the Space Station Freedom baseline. It maximizes the use of the current systems and hardware. The electrical power system and guidance, navigation and control systems remain unchanged. Option B modifies the data management system and the communication and tracking system, and makes minor modifications to the environmental control and life support system and the thermal control system.

Structures And Mechanisms

The structures and mechanisms for Option B are the same as used for Space Station Freedom. These include common berthing mechanisms, pressurized mating adapters, the unpressurized berthing adapter, radiator and solar array deployment mechanisms and truss ports.

The common berthing mechanism mates pressurized elements together. The standard design for the common berthing mechanism minimizes development cost and allows flexibility in arranging the pressurized modules. Each node has six common berthing mechanisms, the International Partner and logistics modules all have one each, and the United States laboratory and habitation modules both have two. Both Soyuz vehicles will require an adapter to mate with node 1.

The pressurized mating adapter and unpressurized berthing adapter serve as the docking ports for the orbiter. Prior to flight 6, the orbiter attaches to the unpressurized berthing adapter located at the end of the truss. After flight 6, with delivery of the United States laboratory, Option B provides two pressurized mating adapters, one primary and one backup.

Deployment mechanisms unfurl and retract the solar arrays and radiators from the truss segments. Extravehicular activity crew must manually pull out the solar array canisters and rotate the "blanket" boxes from the stowed, launch configuration. A deployment mechanism then automatically extends the mast and unfolds the solar arrays. The two external active thermal control system radiator wings have three panels, each with its own deployment mechanism. Each pair of solar arrays has a radiator panel with a deployment mechanism. All deployment mechanisms have a manual override in case of failure.

The truss ports provide structural support and utility transfer for all items stored on the truss, such as unpressurized logistics carriers, gas conditioning assemblies, propulsion modules and attached payloads. To minimize development cost, all truss ports use the propulsion module attachment system. The truss port locations are the same for Option B as Space Station Freedom except the unpressurized logistics carriers will now sit on a different truss segment and one of the attached payload port has been relocated.

Electrical Power System

The electrical power system generates, stores and distributes power to systems, elements and payloads. The silicon cell solar arrays generate 160 volts (nominal) DC primary power. DC to DC converter units convert the primary power to 120 plus or minus 3 volts DC secondary power for distribution to the systems, elements and payloads. The physical locations of the electrical power system hardware and a functional block diagram of the electrical power system architecture are shown in Figure 53.

Option B utilizes the Space Station Freedom baseline electrical power system architecture and photovoltaic module design. The electrical power system employs a channeled architecture with each of the two primary power channels per photovoltaic module rated at 9.375 kW. The DC to DC converter units provide the conversion from primary to secondary power. The DC to DC converter units output 6.25 kW at 120 volts direct current and DC to DC converter units may be used in parallel to support 12.5 kW loads. The baseline electrical power system architecture and solar power module designs are mature, modular and expandable. They are designed to meet all key requirements, such as fault tolerance, power quality, power rating and power capability. The critical design review for the baseline electrical power system has been held. Orbital replacement unit development tests and analyses are complete and fabrication of qualification hardware has begun for the solar array panels, radiator tubing and panels, coldplates and structure.

The solar power module consists of the power generation and energy storage hardware, the photovoltaic active thermal control system and primary and secondary structure outboard of the alpha joints. At Permanent Human Capability, the starboard solar power module consists of one photovoltaic module, and the port solar power module consists of two photovoltaic modules. The power generation hardware lies outboard of the alpha joints, while most of the management and distribution hardware lie inboard of the alpha joints. The alpha and beta gimbals provide full Sun tracking to the solar arrays. With a full complement of batteries, each photovoltaic module nominally produces 18.75 kW, 120 volts DC continuous and 25 kW peak power at beginning of life plus five years. Figure 54 shows the power output as a function of time. Table 23(a) shows current estimates of beginning of life plus five-year power capability. Figure 55 shows the continuous power capability for each stage.

Thermal Control System

The thermal control system maintains systems, elements and payloads within required temperature limits. It uses both active and passive means to control temperatures and manage heat loads generated by power consumers, environment, crew and chemical processes (Figure 56).

The passive thermal control system utilizes coatings, insulation, isolators, heaters and passive radiators to maintain temperatures. The active thermal control system uses fluid loops to acquire, transport and reject waste heat. These systems provide two failure tolerance to critical systems and one failure tolerance to life support functions from flight 6 through flight 10. After flight 10, Option B has full two failure tolerance to all critical functions.

The passive thermal control system coatings enhance heat absorption to minimize heater power or enhance heat loss. Multilayer insulation isolates surfaces from their environment.

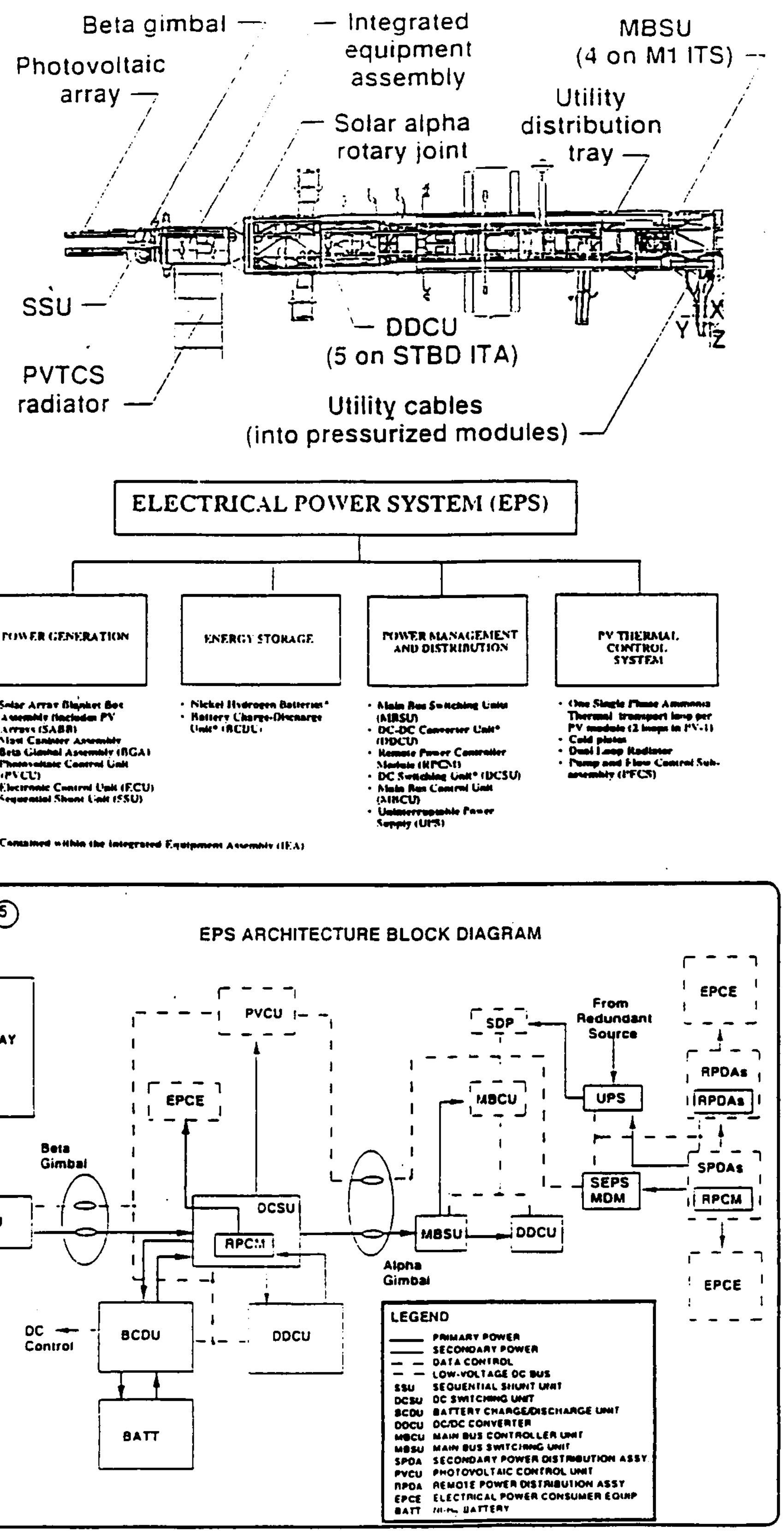


Figure 53
Electric power system

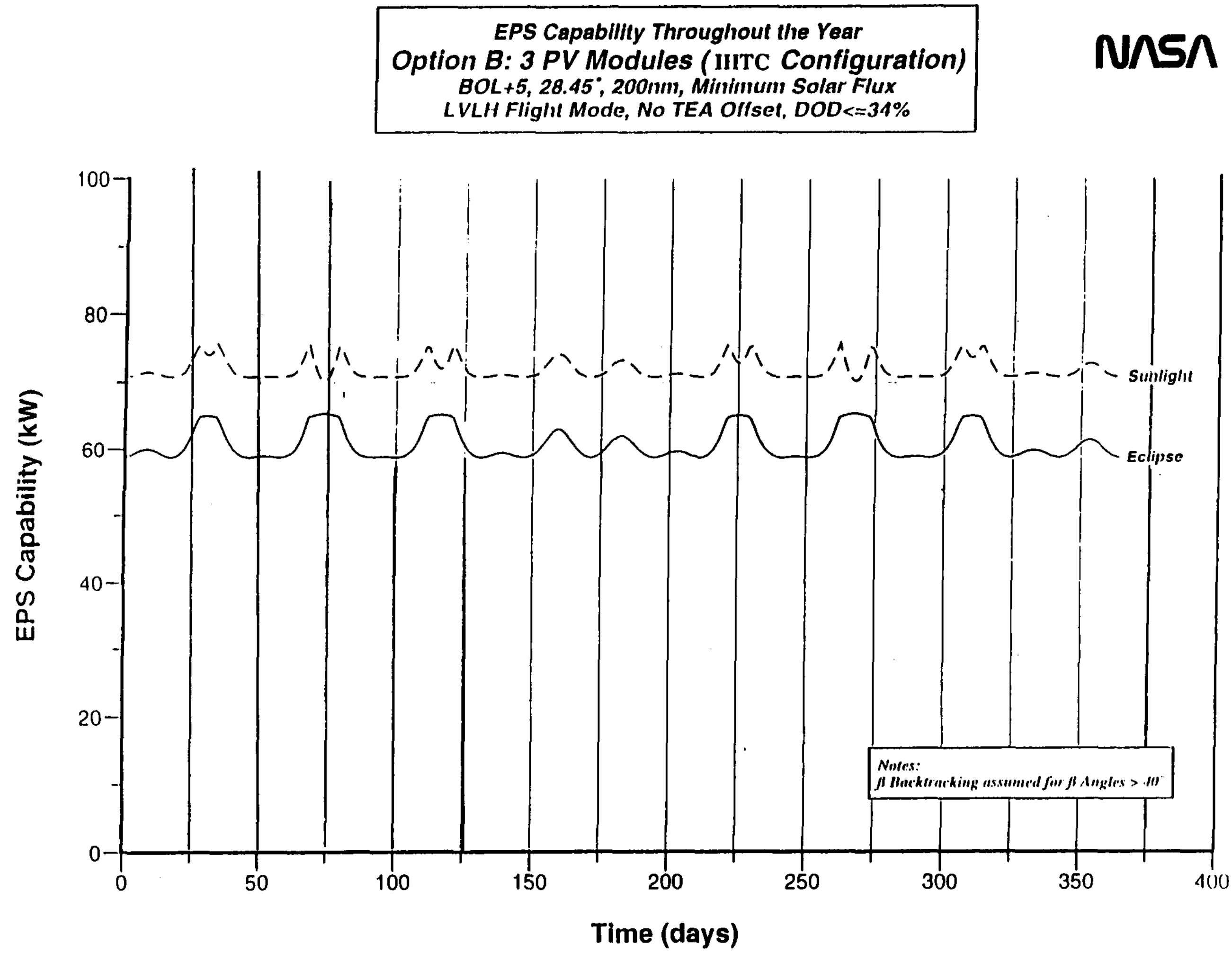


Figure 54
Electrical power system power generation profile - International Human Tended Capability configuration

Applications include the pressurized module exterior shells and the low temperature internal water lines. These heaters prevent freezing for hydrazine in the propulsion modules. Passive radiators are used to reject heat from external avionics.

The active thermal control system consists of the external, the internal and the photovoltaic active thermal control system. The external active thermal control system consists of three, two phase ammonia loops (one moderate temperature and two low temperature loops). Major components include heat exchangers, coldplates, pumps, ammonia tanks and rotating, direct condensing radiators. The moderate temperature loop can operate as a low temperature loop to provide redundancy to life support functions. The external active thermal control system can reject 27.8 kW of heat at Human Tended Capability (41.8 kW using the third radiator orbital replacement unit) and 95.6 kW at Permanent Human Capability. The internal active thermal control system consists of two, single phase water loops in each pressurized element (one moderate and one low temperature loop) cross connected for redundancy. Major components include pump modules, coldplates, heat exchangers and flow control assemblies. The photovoltaic active thermal control system consists of two, single phase ammonia loops on photovoltaic-1, and one loop on photovoltaic-2 and photovoltaic-3. Major components include coldplates, pumps, flow control assemblies and radiators. Each photovoltaic active thermal control system can reject 8.4 kW

Table 23
Option B payload power

a) Option B Orbit Average Power

No. of PV Modules	Orbit Average Power (kW)
1	23.5
2	46.9
3	68.3

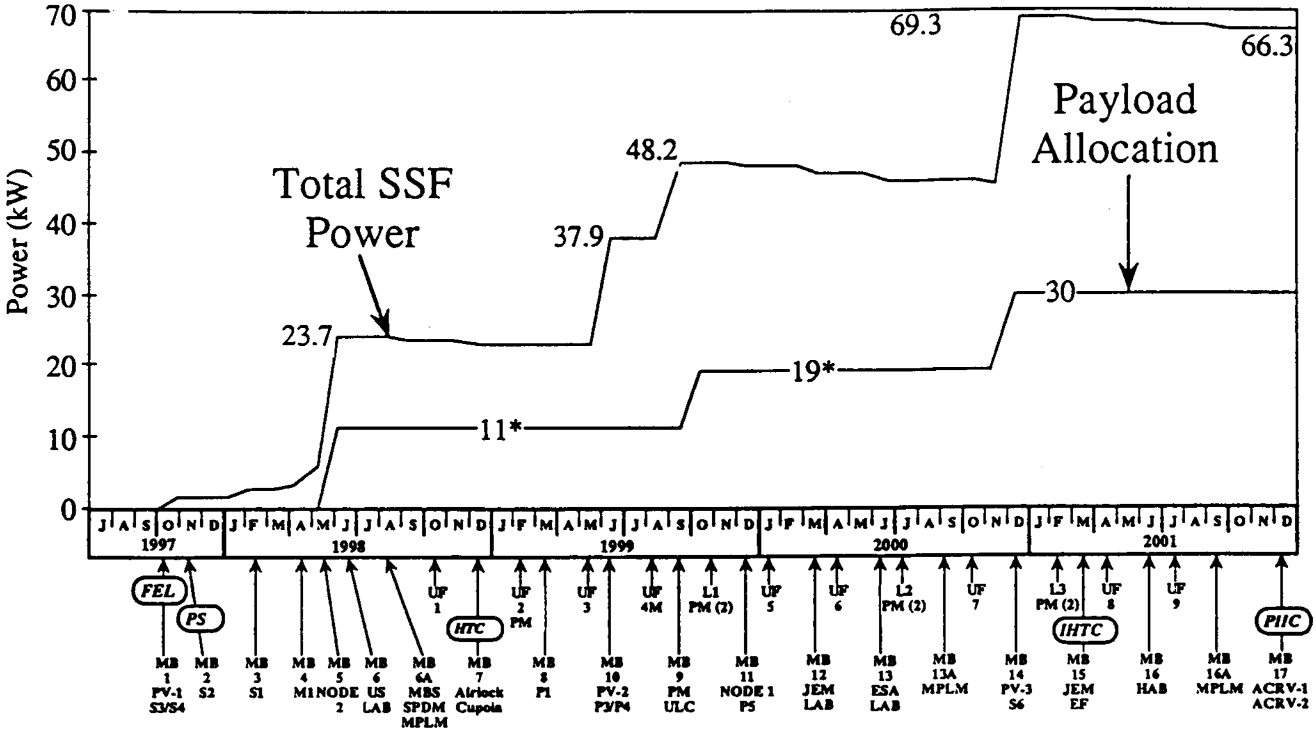
Orbit Average Power is for an EPS at BOL + 5 Years, Using an Average Yearly Eclipse Time and a Full Complement of Batteries/BCDUs.

b) Option B Continuous Stage Power

Milestone	Power Capability (kW)	Station Housekeeping Power	Available To Payloads A	Available To Payloads B	Payload Allocation
PS	18.8*	2.4	N/A	8.0	11
HTC-S	23.6	10.4**	13.2	8.5	11
IHTC	68.2	23.1**	45.1	40.6	30
PHC	66.3	28.0**	38.3	N/A	30

Stage Power is specific to the Option B assembly sequence

*2/3 Battery/BCDU complement
**Assumes 14.7 psi inside station
A: No power transfer to the Orbiter
B: 20-day Orbiter mission with power transfer



* Add 2 kW when unmanned

Figure 55
Payload power availability through Permanent Human Capability

orbit average and 12 kW peak waste heat generated by the photovoltaic module equipment.

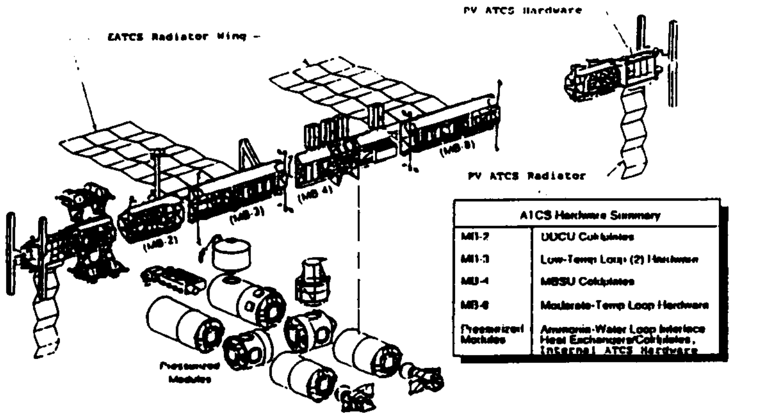
The thermal control system is built and operated in increments starting with the launch of the photovoltaic-1 active thermal control system, fully charged with ammonia, on flight 1. All components on truss segments S3 and S4 are passively cooled until electrical power system and photovoltaic active thermal control system activation on flight 2. Principal low temperature external active thermal control system components launch dry (to reduce mass and complexity) on flight 3 and require nitrogen from the gas conditioning assembly on flight 4 to force ammonia from the storage tanks into the fluid lines.

Option B does not significantly alter the thermal control system design, adding only one avionics radiator on segment S2 to accommodate an additional external standard data processor. Option B has high power and long fluid lines that favor development of two-phase technology to minimize power and weight. The design is mature; some components (e.g., the photovoltaic active thermal control system coldplates and radiators) have completed critical design reviews and begun manufacture of flight hardware.

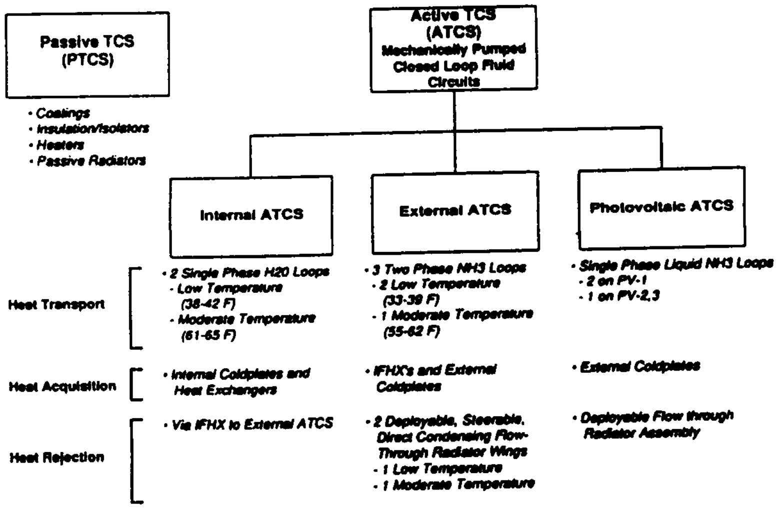
Propulsion System

Propulsion for Space Station reboost, attitude control and final docking with the orbiter is provided by the propulsion modules that utilize hydrazine as a monopropellant. Each propulsion module fluid system is self contained with no fluid connections to the Space Station or other propulsion modules. The modules are delivered to the Space Station fully loaded or partially loaded, depending on the optimum payload manifesting for the particular Space Shuttle mission. The first two propulsion modules are brought up on flight 2 and attached to the truss segment, just inboard of the alpha joint. The modules contain the necessary propellant, thrusters and avionics to provide thrust for reboost and attitude control. The propulsion modules consist of a mounting structure and a cluster of six series propellant and pressurant tanks. The structure

a) Active TCS Major Components



b) Active TCS Subsystems



c) Active TCS Architecture

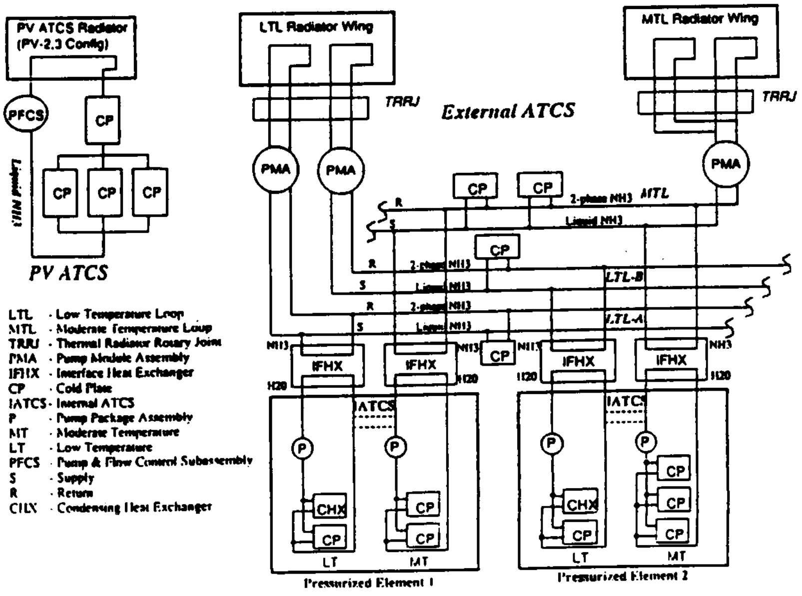


Figure 56
Thermal control system at Permanent Human Capability

provides for the mounting and support for all module components, a mechanical interface with the truss assembly, and a mechanical interface with the orbiter for launch and return. The propulsion module pressurized volumes (tanks and fluid lines) are considered safety-critical hardware and thus have micrometeoroid and orbital debris protection. Attach systems provide the propulsion module mechanical, structural and umbilical attachment to the truss. There are eight module locations. The total number of propulsion modules on-orbit is based on operational and logistics considerations. The modules are returned to the ground for refueling.

Guidance, Navigation and Control System

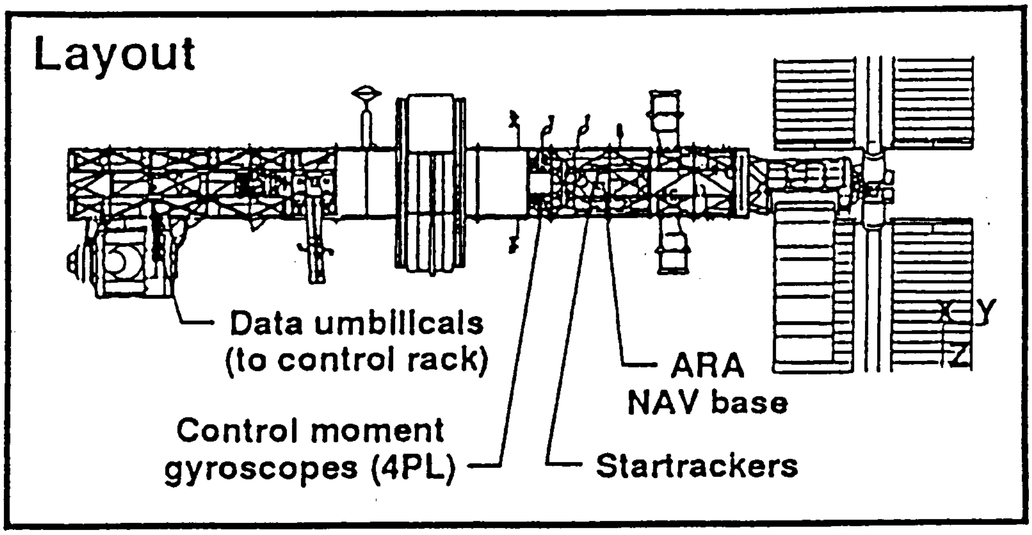
The guidance, navigation and control system computes orbital reboost and collision avoidance maneuvers, determines attitude and attitude rate, and computes pointing information for communication and tracking (Figure 57). The system consists of the four control moment gyros, three inertial sensor assemblies, two star trackers, one navigation base and four passive magnetic dampers. It activates the control moment gyros on flight 2 to support Power Station and does not significantly modify guidance, navigation and control.

Data Management System

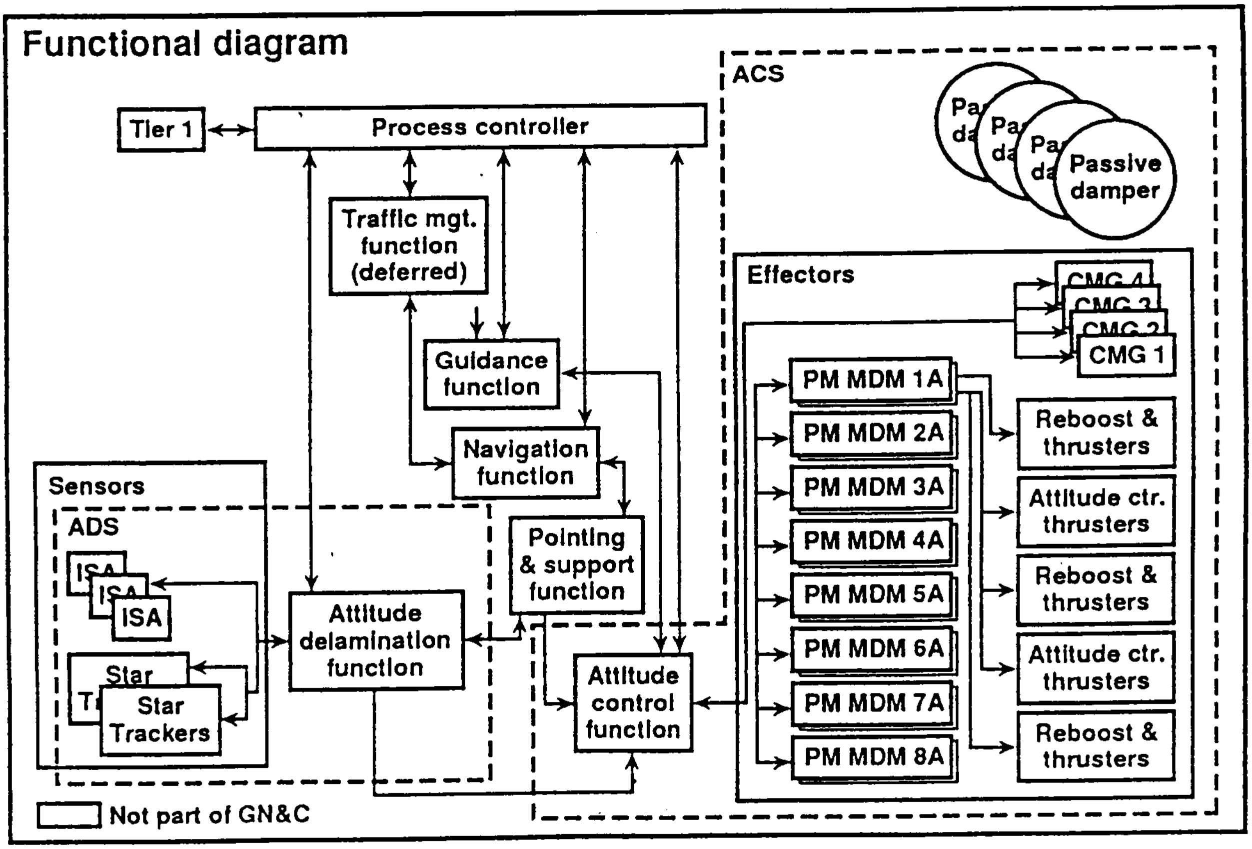
The Option B data management system architecture (Figure 58) retains the same software and hardware components as the Space Station Freedom baseline. This approach takes maximum advantage of the completed Space Station Freedom baseline development work. The hardware and software are at critical design review, and Option B requires no new component or software design work. Option B separates the external and internal system control functions and eliminates the separate payload fiber optic network. Option B also simplifies the user support environment, the network operating system,and the master object database manager. The configuration selected deletes the printers and the separate emergency management and distribution system.

Option B places all systems mounted on the truss under the control of external data management system components. Separate data management system components control the avionics in the pressurized elements. This separation simplifies verification by allowing separate facilities for truss and pressurized element avionics verification. The external data management system components control all station survival functions without reliance on the active thermal control system, or on the systems that make up the pressurized volumes. This reduces the number of orbital replacement units required for station survival by over 50 percent, enhancing the overall station reliability and availability. Two failure tolerance for data management system starts at flight 2, versus flight 6 for the Space Station Freedom baseline.

Elimination of the payload fiber optic network deletes bridges and payload ring concentrators, providing savings in power and mass. United States laboratory payload commanding is via the payload standard data processor over military standard 1553B buses. International payloads are commanded across the fiber optic network gateways. The data management system transfers data among payloads and to the ground via high rate links to the communication and tracking system. Option B simplifies the payload command and control architecture. Increasing the isolation provided between the core and payload systems and minimizing payload verification requirements. Option B replaces the manual fiber optic patch panel, used for high-rate link data transferred to the Ku-band system, with an automated patch panel. This configuration has several advantages over the fiber optic payload network connections and the Space Station Freedom baseline patch panel: lower power and cost per payload connection, increased telemetry bandwidth, remote reconfiguration during tended and untended operations, and high rate link rack to rack communication. External payloads on the truss and United States payloads in international elements are provided access to the payload standard data processor local buses and high rate links routed to the automated patch panel. Portable computers are used for most payload interfaces to minimize local bus traffic. The Option B data management system achieves savings over the Space Station Freedom baseline by the separation of internal and external avionics, which reduces and simplifies the integration and verification tasks and associated facilities. The elimination of the payload fiber optic network reduces hardware, software and verification costs for both assembly and operations.

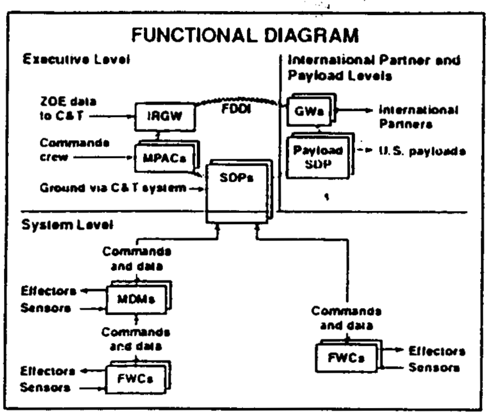


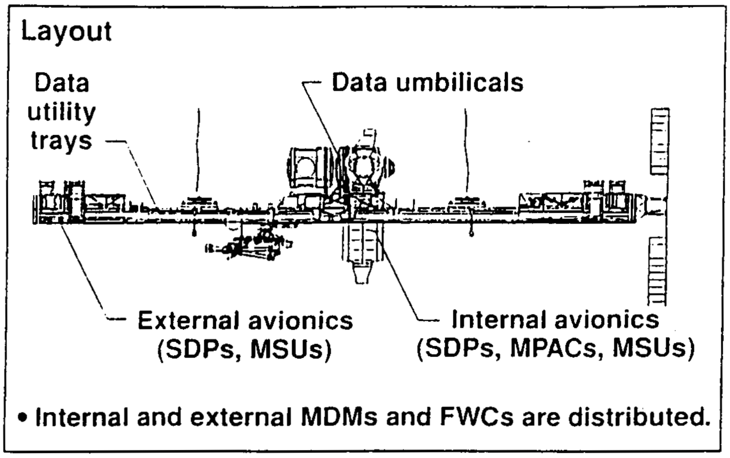
a) GN&C Major Components



b) GN&C Functional Diagram

Figure 57
Guidance, navigation and control system





U.S. DMS

Data Management

MPAC	Multi-Purpose Application Console
MSU	Mass Storage Unit
SDP	Standard Data Processor

Data Acquisition

MDM	Multiplexer/DeMultiplexer
FWC	Firmware Controller

Data Transport

1553	MIL-STD-1553 Bus
APP	Automated Patch Panel
FDDI	Fiber Distributed Data Interface
GW	Gateway
HRL	High Rate Link
IRGW	Intermediate Rate Gateway

International Partners

APM	(Columbus) Attached Pressurized Element
CVPS	Columbus Payload Video System
JEM	Japanese Experiment Module
MUX	Multiplexer
PP	Patch Panel

OPTION B
DMS CORE AND PAYLOAD ARCHITECTURE

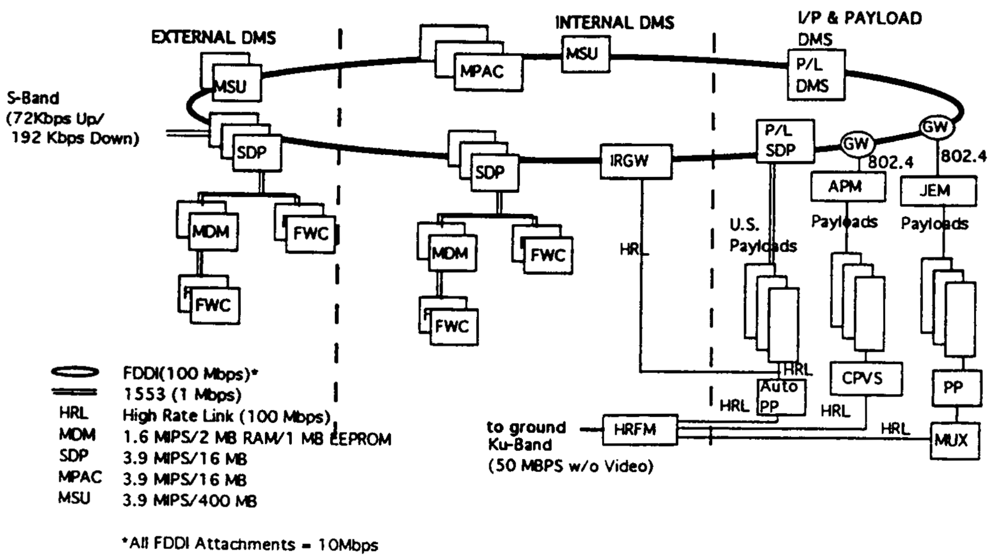


Figure 58
Data management system

Communications and Tracking System

The communications and tracking system uses an assembly contingency subsystem, a space-to-ground subsystem, a video distribution subsystem, an internal audio distribution subsystem and an ultra-high frequency communications subsystem (Figure 59).

The assembly contingency subsystem is a single-fault tolerant, S-band communications link between the station and the ground via the Tracking and Data Relay Satellite System. The Space Station Freedom baseline provided command, control and telemetry data transfers between the ground and the station, along with two channels of full duplex audio. Option B changes the formatting used for data and audio. Baseline formatting utilized a packetized data transfer protocol, and audio conversion provided 9.6 kbps of digitized audio per channel (19.2 kbps total for two channels). The Option B approach uses bitstream data formatting similar to the Space Shuttle program and uses the Space Shuttle program audio conversion at 32 kbps per channel (64 kbps total for two channels).

Option B reduces the amount of data bandwidth available when audio channels are utilized by requiring 64 kbps for audio. The Space Station Freedom baseline provided 172.8 kbps of downlink and 52.8 kbps of uplink (including overhead) when audio channels were active. Option B will now provide 128 kbps of downlink and 8 kbps of uplink when audio is active. The savings with Option B is the ability to utilize existing mission and payload control systems.

The space-to-ground subsystem is a zero-fault tolerant, single string Ku-band communications downlink from the station to the ground via the NASA Tracking and Data Relay Satellite System. The baseline capability allowed up to 43.2 Mbps of payload data and video data (up to four channels) to be sent to the ground by using a packetized data transfer protocol. Option B will use the same data format as in the Space Shuttle program. This formatting change will allow a higher usable data bandwidth for payloads; 48 Mbps for payload data only or 2 Mbps for payload data when video is transmitted. Another change will be to utilize direct FM transmission of video instead of a digitized approach. This change will capitalize on existing Space Shuttle program ground systems capable of handling data and FM video.

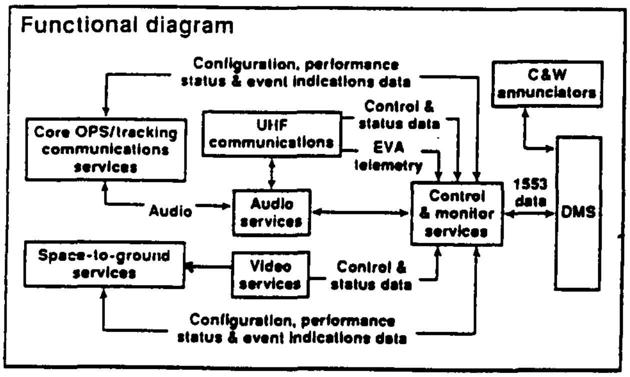
The video distribution subsystem is a zero-fault tolerant system used for distributing onboard television camera views to monitors and recorders and for transmission to the ground. Space Station Freedom baseline used a digitized, fiber optic distribution of internal and external camera views. Option B utilizes the same technology but changes to Space Shuttle program camcorders (internal), reducing the amount of units from seven to four (two at Human Tended Capability and four at Permanent Human Capability) external camera port locations from 14 to 10 (five at Human Tended Capability and 10 at Permanent Human Capability) and the distribution video switches (internal: from six to four; external: from three to two).

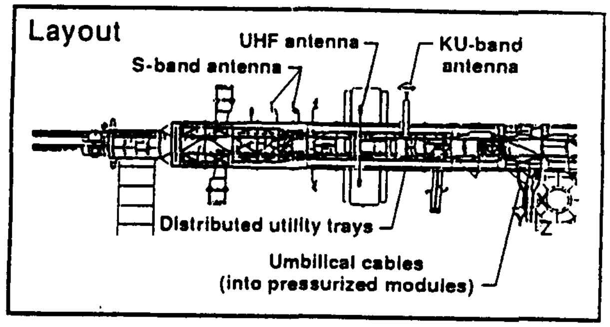
The internal audio subsystem provides audio and voice communications between the crew members, docked orbiter and the ground. The Space Station Freedom baseline has a single-fault tolerant (two strings) system with both a wireless audio capability and a distributed audio capability using fiber optic technology. Space Station Freedom baseline audio was also responsible for caution and warning annunciation in a one-fault tolerant environment. Option B reduces the international audio subsystem to zero-fault tolerant (one string), wireless only audio intercommunications. Option B uses a single fault tolerant set of Space Shuttle program derived caution and warning annunciators, and provides a redundant direct microphone plug-in capability for voice communications with the ground via S-band interfaces. The ultra-high frequency communication subsystem provides space-to-space communications of audio and data (8 kbps) between two extravehicular activity crew members, and between extravehicular activity crew members and the orbiter, and between the orbiter and the Space Station when in close proximity. The Option B ultra-high frequency communication subsystem is the Space Station Freedom baseline.

Environmental Control and Life Support System

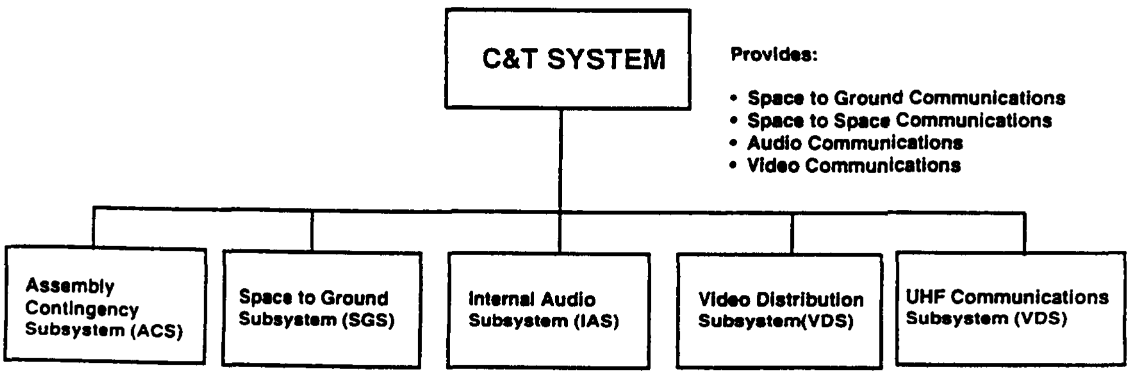
The environmental control and life support system provides the habitable environment for the crew. The environmental control and life support system is composed of six subsystems: atmosphere control and supply, atmosphere revitaliza-

COMMUNICATIONS AND
TRACKING SYSTEM
(C&T)





a) C&T Functional Diagram



Assembly Contingency Subsystem (ACS)
- Dual String S-Band Communications via TDRSS
- 72/192 Kbps Forward/ Return link
- Command, Control, Telemetry & Audio data transfers
- Ground Tracking Support

Space to Ground Subsystem (SGS)
- Single String Ku-Band High Data Rate Downlink via TDRSS
- 50 Mbps Return Link
- Payload Data and/or up to four video channels

Internal Audio Subsystem (IAS)
- Eight channel wireless audio distribution
- Fiber Optic distribution technology
- Two channel full duplex audio to ground communications
- EVA, Orbiter and Ground Audio Intercommunications

Video Distribution Subsystem(VDS)
- External and Internal video camera viewing
- Simultaneous video generation & display
- Fiber Optic Video Distribution technology
- Up to four channels routed to ground via SGS
- Full support to Payloads and Internationals

UHF Communications Subsystem (VDS)
- Simultaneous Voice & data communications
- Five channel full duplex audio
- Station coverage zone to within 5 kilometers

b) C&T Major Components

Figure 59
Comunications and tracking system

tion, fire detection and suppression, temperature and humidity control, water recovery and management, and waste management. Figure 60 shows the environmental control and life support system functional schematics for Permanent Human Capability.

Under the Space Station Freedom baseline, all Human Tended Capability environmental control and life support system equipment and software has started long-lead fabrication to support flight hardware delivery schedules. The Human Tended Capability environmental control and life support system hardware and software will be qualified for delivery beginning in 1994 and early 1995.

The atmosphere control and supply subsystem provides oxygen and nitrogen pressure control, vent and relief, oxygen and nitrogen storage and distribution, gas conditioning and pressure equalization. Cryogenic oxygen and nitrogen flows into the gas conditioning assembly where the gases are regulated and thermally conditioned prior to entry into the habitable volumes. Then the gases are distributed to the element use points. Vent and relief hardware provides the capability to avoid both over and under pressurization of the habitable volumes.

The atmosphere revitalization subsystem monitors and controls the level of carbon dioxide and trace contaminants in the cabin air. A four-bed molecular sieve removes carbon dioxide from the cabin air and vents the carbon dioxide to space. The major constituent analyzer monitors the partial pressure of major constituent gases. The trace contaminant control system removes excess trace contaminants. At Permanent Human Capability, a trace contaminants monitor will measure trace gases and total particulate count. There are provisions to allow growth to closed loop oxygen recovery after Permanent Human Capability.

The trace contaminants monitor and the crew health and environments system volatile organic assembly measure about the same trace gases but to different concentrations.

The fire detection and suppression subsystem sensors detect the smoke in an element enclosed volume. The power and airflow to that enclosed volume is automatically shut off. Then the carbon dioxide fire suppressant floods the enclosed volume and extinguishes the fire. Portable carbon dioxide extinguishers are used to manually suppress fires in the cabin open volume. The fire detection and suppression remains unchanged from the Space Station Freedom baseline except for the deletion of the flame detector.

The temperature and humidity control subsystem provides for the control of cabin temperature, humidity, air particulates, micro-organisms, intermodule ventilation and avionics air cooling. Intermodule ventilation is provided between adjoining station pressurized elements to circulate air for the crew.

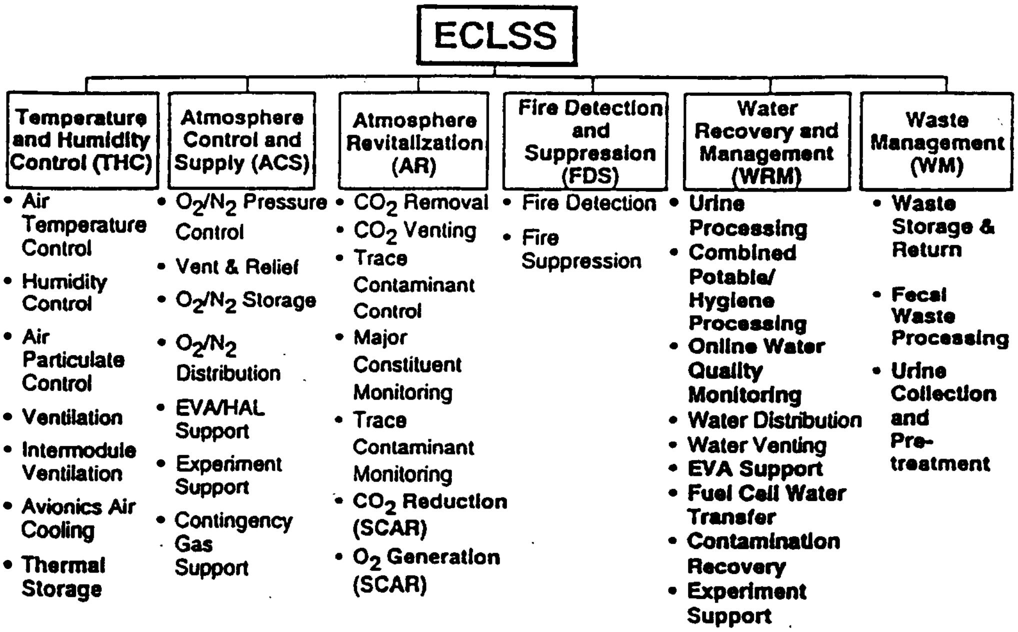
The water recovery and management subsystem recycles water to reduce the amount of water that must be resupplied to the station and the waste water that must be returned from the station. This subsystem consists of equipment to recover water from hygiene sources (i.e., clothes washer and dryer, shower and hand wash), from the urine and flush water, from cabin condensate, the extravehicular mobility unit, and fuel cell water supplied by the orbiter. The water recovery and management restores system cleanliness after contamination and vents excess water. During Human Tended Capability, however, the system only provides the capability for condensate storage with overboard venting. The orbiter provides the remaining functions. Option B deletes the sterilizer.

The waste management subsystem collects and stores the crew metabolic wastes. Prior to Permanent Human Capability, the waste management functions are provided by the orbiter. At Permanent Human Capability and beyond, commode facilities collect and store the waste. Urine and flush water equipment collect this waste for subsequent processing in the waste recovery and management subsystem.

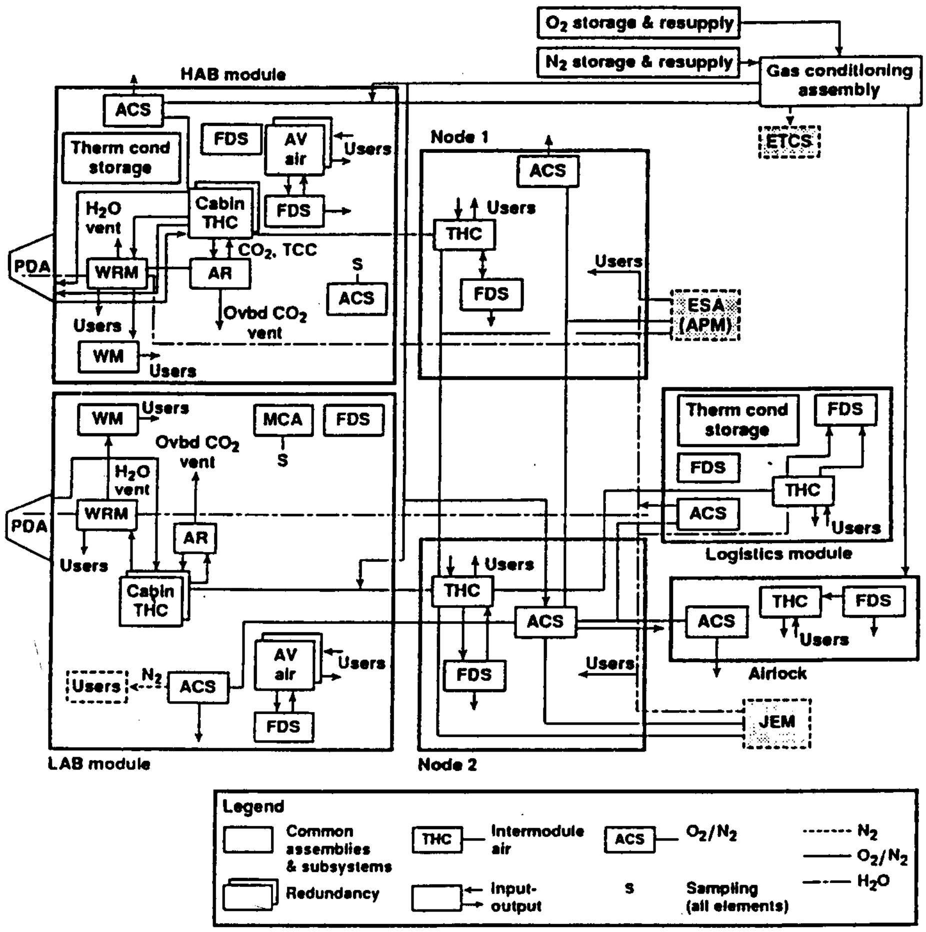
The environmental control and life support system provides the vacuum exhaust system, vacuum resource system and nitrogen distribution to the payloads for experiments. Nitrogen is plumbed from the module umbilicals to the International Standard Payload Racks for experiment usage. The vacuum exhaust system provides removal of waste gases generated by payloads and facilities. The vacuum resource system gives the payload access to space vacuum for purposes other than removal of bulk waste gases.

Flight Crew Equipment Systems

Flight crew equipment systems consist of equipment that enable safe and comfortable crew habitation and interfaces for a productive and sus-



Environmental Control and Life Support System (ECLSS) Functions



ECLSS FUNCTIONAL SCHEMATIC

Figure 60

Environmental control and life support system Permanent Human Capability tained working environment. Distributed throughout the modules, the flight crew equipment systems provide habitation, operational support, personal hygiene, environmental health assessment, emergency equipment and supplies, housekeeping, inventory management, trash management, photographic and viewing equipment, recreation and off-duty equipment and stowage. Option B does not modify the flight crew equipment systems.

Extravehicular Activity System

The extravehicular activity system provides the capability for the crew to perform planned and contingency tasks in an unpressurized environment. The extravehicular activity system supports external maintenance, repair, and inspection of systems and elements. The extravehicular activity system consists of Space Shuttle Program space suits, exercise equipment, airlock and depressurization and repressurization controls, translation and mobility aids, and extravehicular activity tools. The airlock contains most of the extravehicular activity system equipment, with the rest distributed among the other elements. Option B does not modify the extravehicular activity system.

Automation and Robotics

The Option B approach to assembly and maintenance operations is quite similar to the Space Station Freedom approach, consequently the robotics systems are the same. The Canadian Mobile Servicing System performs assembly and maintenance functions across the entire station. It includes the Special Purpose Dexterous Manipulator, the Space Station Remote Manipulator System, the Mobile Base System and the Mobile Transporter. The total system is used for assembly and maintenance of large objects such as truss segments, pressurized modules and logistics elements. The Special Purpose Dexterous Manipulator performs operations on smaller components, such as orbital replacement units and covers, reducing the need for extravehicular activity. The Mobile Servicing System Maintenance Depot provides a place to store spares. There are several power data grapple fixtures on the truss and pressurized modules to allow the Mobile Servicing System to transport itself and its payloads to all assembly and maintenance worksites.

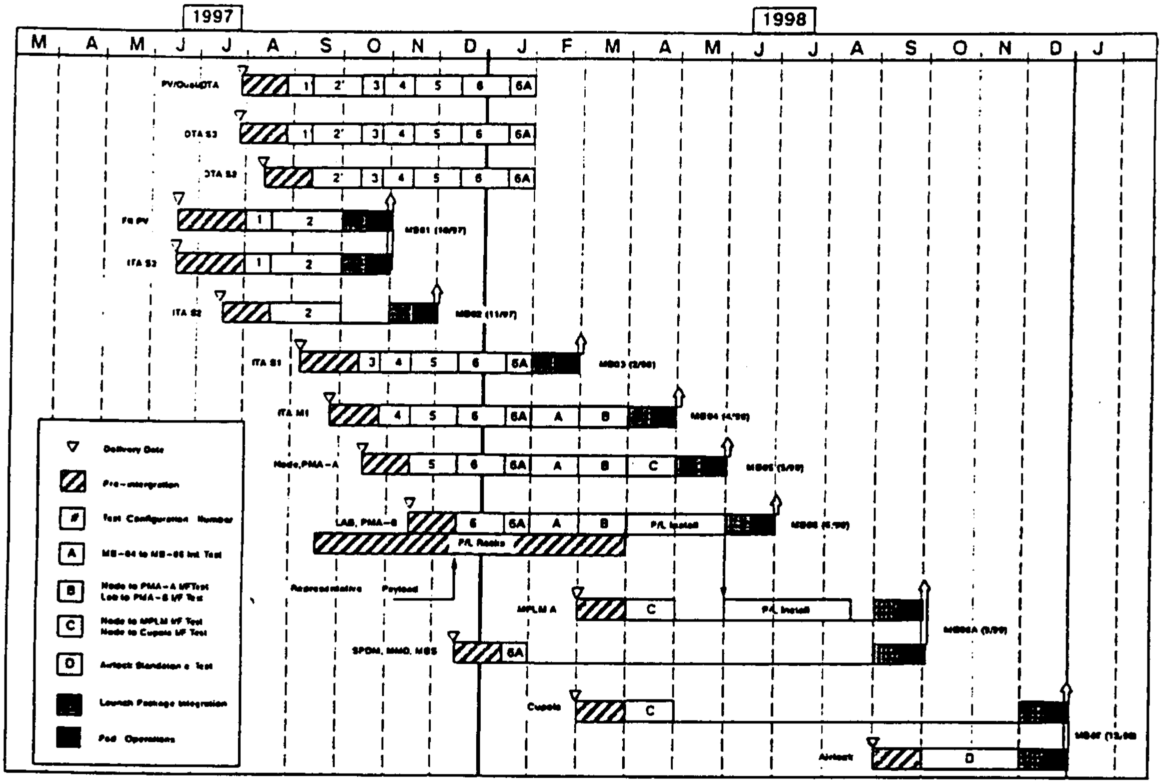
Similarly, the Japanese Experiment Module Remote Manipulating System is retained in its baseline form. This system, consisting of a main arm (similar to the Orbiter Remote Manipulator System) and a dexterous small fine arm, supports assembly and maintenance functions locally on the Japanese Experiment Module Pressurized Module and Exposed Facility.

Manufacturing Considerations

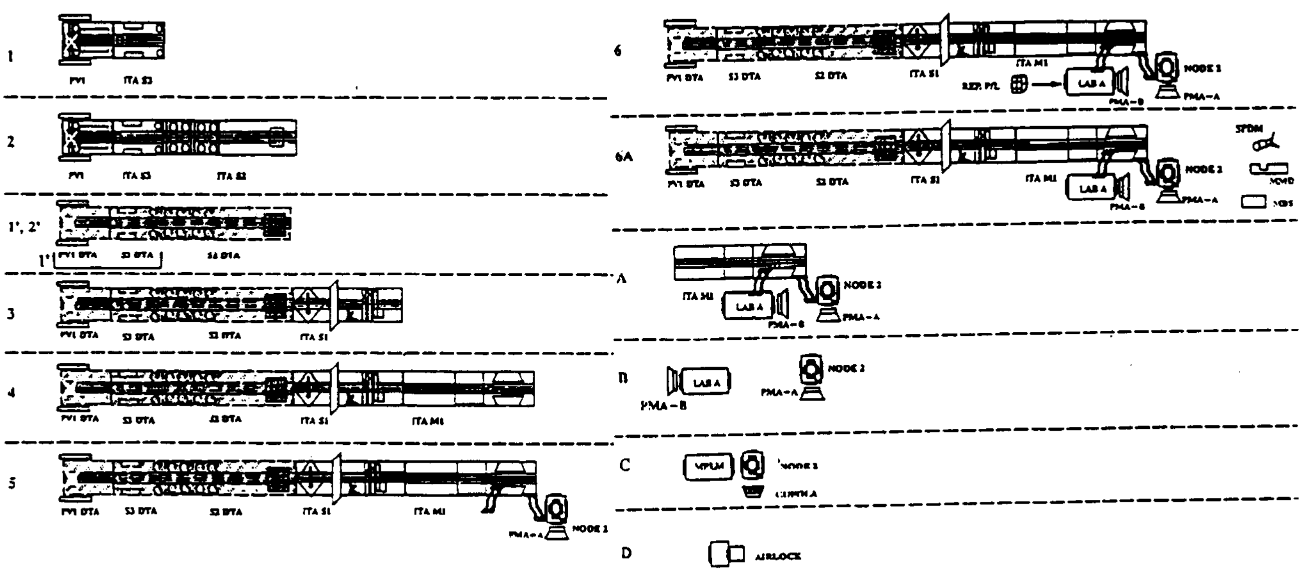
Activities to build the Option B flight elements will be accomplished much the same as the baseline station except for two significant changes involving nodes and airlock. In the baseline, two contractors build, outfit and checkout pressurized modules, which results in duplication of capabilities. Option B splits control functions into loosely coupled external and internal systems, and allows a separation of integrated testing and verification not practical in the Space Station Freedom baseline.

Test and Verification

With few exceptions, the verification approach developed and implemented for the baseline applies directly to Option B. Figures 61 and 62 show the verification process from the identification of requirements to close-out and certification. Program Master Verification Requirements and the Master Verification Plan have been baselined. The Master Verification Database has been developed and implemented to support the verification and certification process. A number of test facilities across the program are in use for system and element development testing. These and other Space Station Freedom baseline facilities and test capabilities coming on-line will be used for qualification and acceptance tests. Twenty-nine major facilities will be involved in systems and software integration and tests. Of these, 25 are involved in hardware and software development, test and verification, and the rest are element acceptance and launch package integration facilities that support flight article verification. Kennedy Space Center has facilities for launch package integration, stage integrated test and Space Shuttle testing.



a) Cargo Integration and Flight Processing Through MB-7



b) Combined Element Integration Test Configurations

Figure 61
Ground processing flow and stage testing configurations

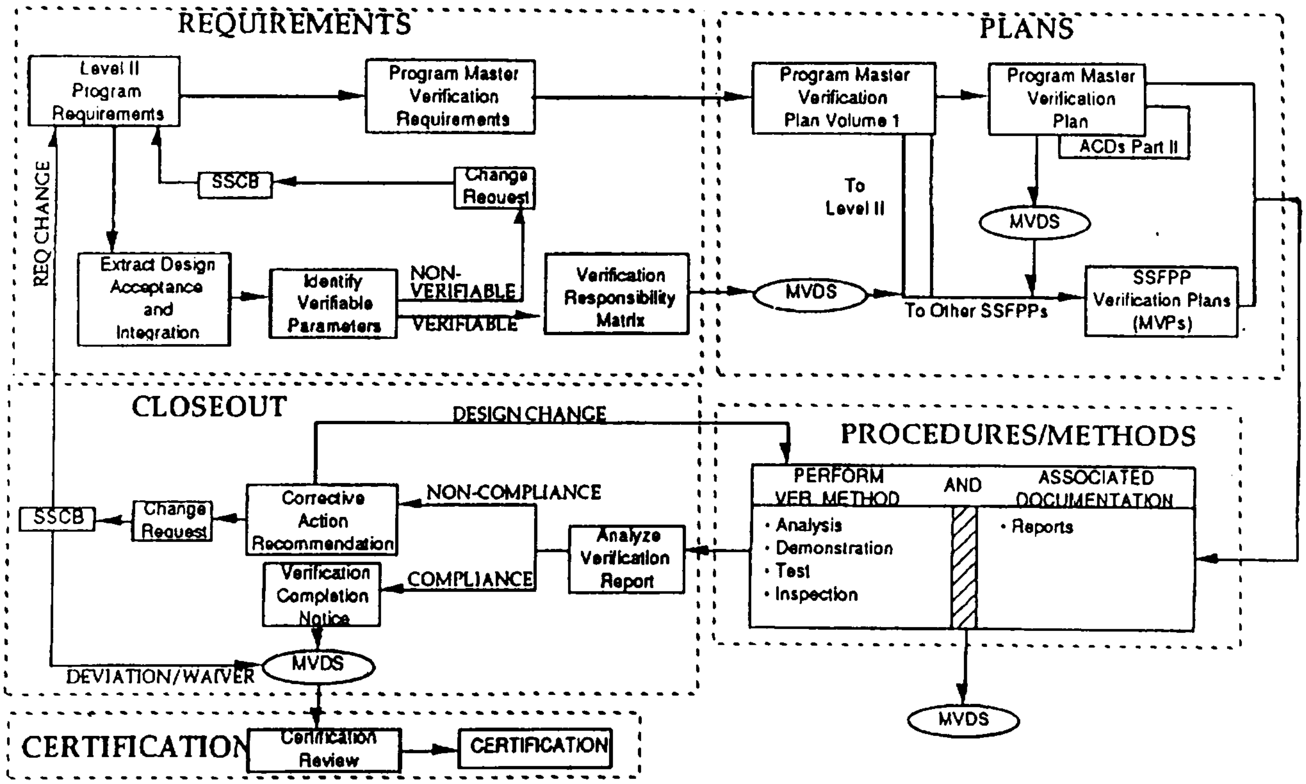


Figure 62
Option B launch package verification process flow

In the Space Station Freedom baseline, avionics systems and software are integrated and tested in a Central Avionics Facility located at Johnson Space Center. The facility contains that complement of external and internal avionics systems and simulations for other station systems needed for systems and software integration and testing. The Option-B avionics architecture partitions station functions into loosely coupled external and internal systems. This split architecture allows Option B to downsize the central facility at Johnson Space Center for integration and testing of external systems. It also allows utilization of the United States laboratory element test article and the node avionics simulator for internal systems at Marshall Space Flight Center. The hardware and software integration of the external to internal systems will be accomplished via a fiber data distribution interface link between the Johnson Space Center facility and the United States laboratory element test article and node avionics simulator for functions that are not time critical. If required, an internal flight processor and appropriate software load located at the Johnson Space Center facility will be used to integrate time critical functions. This approach will increase the fidelity of avionics integration and testing by utilizing the actual hardware sensors and effectors in the United States laboratory element test article rather than simulations. Option B realizes a cost saving from the Space Station Freedom baseline due to the reduction of hardware and simulations by utilizing the United States laboratory element test article.

Factory sites will perform flight article acceptance testing. The combined test team will eliminate post delivery test and verification at Kennedy Space Center. Kennedy Space Center will handle stage integrated testing for each flight 1 through flight 7. Partitioning internal and external avionics eliminates the need for the node avionics simulator at Kennedy Space Center and Marshall Space Flight Center at the same time. Option B may require an upgrade to an existing Kennedy Space Center flight processor simulator to represent the internal functions for the flight 2 stage test.

Orbiter Modifications

Orbiter modifications required to support Option B are the same as those required for the Space Station Freedom baseline. For example, Option B requires a data interface unit in the aft flight deck for command data with the orbiter while mated; remotely operated electrical umbilicals for transfer of power, command and data on the early flights; assembly power conversion units for power to cargo elements in the payload bay; and an external airlock and docking system. Long-duration orbiters may be used to provide early science capability beginning after flight 2. Two orbiters will be modified and available by 1997 with the capability to support a 20-day mission configured with a Spacelab in the payload bay. Maximum stay time is limited by crew physiology considerations, the orbiter cryogens supply and by the amount of power transferred from the Space Station. User power on the orbiter is restricted to approximately 9.5 kW based on orbiter power distribution limitations and heat rejection capability. User experiments can be conducted in the mid-deck and Spacelab. Early utilization of long-duration orbiters, flight 2 through flight 5, does not require the external airlock and docking system, but will require modification of the unpressurized berthing adapter to incorporate the Spacelab tunnel and the mating interface. If the external airlock and docking system is installed, the unpressurized berthing adapter must be replaced with a small transition structure attached to the mobile transporter with the passive half of the docking system enabling normal dockings.

Power transfer to the orbiter for long-duration orbiter flights will be provided via orbiter power conversion units on the orbiter. Three orbiter power conversion units are required for long-duration orbiters prior to Human Tended Capability to provide maximum power to the users, who are all assumed to be on the orbiter side of the interface. After Human Tended Capability, Option B requires two orbiter power conversion units.

Integration Factors

Once acceptance testing at the factory has been completed, the flight hardware will be transported to Kennedy Space Center for ground processing prior to launch. The development centers will have engineering support personnel present at the launch site during the processing of their hardware. All nonhazardous elements will be processed through the Space Station Processing Facility and the hazardous elements will be processed through the Propulsion Module Servicing Facility.

Hardware undergoes receiving inspection, post delivery verification, stage testing, launch package integration, off-line Space Shuttle interface testing and, if required, hazardous servicing. Receiving inspection includes reviewing the data packages and inspecting for visible shipping damage. Post delivery verification will functionally verify the hardware at the element and end item level. Stage testing consists of mating the flight 1 and flight 2 flight hardware (S2) to verify stage functionality. Subsequent stages are verified using development test articles for stage 2 and flight hardware for stages 3 through 6A. See Figure 61 for the ground processing flow and stage test configuration. Launch package integration configures the various elements of an individual flight for installation into the orbiter. Testing verifies the station element-to-Space Shuttle interface prior to integration.

Ground processing includes all experiment-to-rack physical integration. Ground processing also includes an interface verification test between the United States payload rack and attached payloads with the core station. After completing integration activities, the majority of all cargo elements are transported to the pad for vertical installation into the orbiter. Exceptions to vertical installation are installed in the orbiter at the orbiter processing facility.

Performance and Capability

Weight Summary

Option B uses weight data from the Space Station Freedom Program, which has critical design review level of maturity. These data were used in the assembly manifesting process . Since the Shuttle provides approximately 37,800 pounds of useful upmass capability to 220 nautical miles at a 28.8 degree inclination, including orbital support equipment (approximately 6000 pounds) and a reserve (1800 pounds), a typical stage results in the addition of approximately

31,000 pounds of on-orbit mass. Outfitting stages requiring the use of one or more mini-pressurized logistics modules provide somewhat less on-orbit mass because the tare weight of the carrier must be subtracted from the overall mass. Table 24 provides a flight-by-flight breakdown of cargo mass. Figure 63 shows flight summaries of cargo mass with margins included.

Total on-orbit mass is shown in Table 22(b). The values presented in the table include primary structure and payloads delivered by utilization flights. The total on-orbit mass for the Power Station configuration is 67,147 pounds. This total grows to 248,255 pounds with the completion of the starboard truss and addition of node 2 and the United States laboratory for Human Tended Capability. The completion of the port truss and the addition of the International Partner modules brings the total on-orbit mass to 526,986 pounds at International Human Tended Capability. Finally, the habitation module and assured crew return vehicles bring the total Permanent Human Capability mass to 608,166 pounds. A subsystem weight summary is shown in Table 25.

Power Summary

The Option B concept sufficiently meets all user power commitments. Table 23 and Figure 55 address power generation and user power availability for this option. Beginning with one photovoltaic array at the Power Station capability, 18.8 kW of total power is generated with 8.0 kW available to users for a 20-day orbiter mission. Once Human Tended Capability is achieved, 23.6 kW of power is generated with 13 kW

Table 24
Option B cargo mass by flight

Flight Number	Cargo Mass (lbs)	Mass Margin (lbs)
1	36689	+77
2	30458	+583
3	31646	+520
4	31018	+1249
5	26572	+1725
6	31054	+26
7	21139	+5867
8	19679	+8328
9	28968	+2513
10	32119	+62
11	28783	+19
12	23409	+6193
13	30172	0
14	30176	0
15	16000	+99
16	27110	+3371
17	28101	0
18	30120	0
19	16000	+99
20	35060	-5575

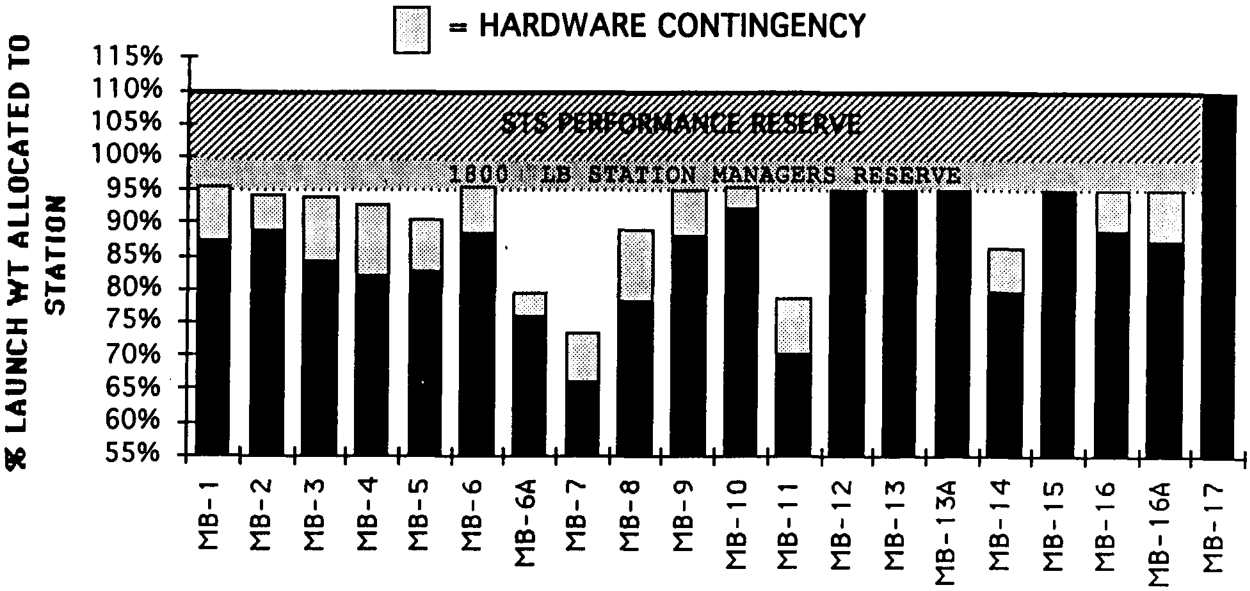


Figure 63
Launch weights for Option B assembly sequence (28.8)

Table 25
Option B subsystem weight summary

	Launch Weight (lb)	
	Space Station Freedom	Option B
Data Management System and Application Software	10,341	9,241
Electrical Power Generation	34,852	34,852
Power Distribution and Control	29,193	29,193
Communications and Tracking	3,323	2,168
Environmental Control and Life Support	19,304	19,304
Thermal Control	33,399	33,399
Flight Crew Equipment Systems	10,767	10,767
Propulsion	29,412	29,412
Secondary Structures	166,623	166,623
Mechanical Systems	38,418	38,418
Guidance and Control	2,819	2,819
Extravehicular Activity	9,202	9,202
Consumables	30,292	30,292
Total	417,945	415,690

Table 26
Option B subsystem power summary

	Housekeeping Power (kW)	
	Space Station Freedom	Option B
Data Management System and Application Software	3.48	3.53
Electrical Power Generation	-	-
Power Distribution and Control	1.48	1.48
Communications and Tracking	1.06	1.60
Environmental Control and Life Support	5.41	5.41
Thermal Control	1.70	1.70
Crew Health Care	0.32	0.32
Flight Crew Equipment Systems	1.43	1.43
Propulsion	0.90	0.90
Secondary Structures	0.00	0.00
Mechanical Systems	0.20	0.20
Guidance and Control	0.53	0.53
Extravehicular Activity	0.01	0.01
Utilities	0.00	0.00
Consumables	0.00	0.00
Margin	0.79	0.79
Total	17.31	17.90

available to users with no power transfer to the orbiter, or 8.5 kW if power transfer to the orbiter is required. At the International Human Tended Capability with the second and third photovoltaic arrays present, 68.2 kW are generated and the user power is increased to 45.1 kW with no orbiter power transfer or 40.6 kW with orbiter power transfer. After the United States habitation module and assured crew return vehicles are added to establish Permanent Human Capability, the level of user power remains sufficiently high at 38.3 kW. A subsystem power summary is given in Table 26.

Option B's key attribute to high power is the incorporation of both alpha and beta joints to provide full Sun tracking to the solar arrays. With this configuration, the highest levels of power can be maintained throughout the orbit and at various flight attitudes while maintaining the required microgravity levels. In addition to high power, the users and International Partners receive the commitment of 120 volts direct current continuous power at their payload interfaces.

Safety and Reliability

The Option B design meets or exceeds all requirements to maintain station and crew survival and orbit integrity for all stages. The overall failure tolerance has been improved by the incorporation of two-fault tolerant avionics system to support critical functions. Because the alpha joint is only single-fault tolerant, two-fault tolerance in the power system is not achieved until the second array is deployed on flight 10. Flight 11 marks the first full two-fault tolerant system capability (power, data, thermal and propulsion) with the delivery of the port propulsion modules.

Current analyses show that the solar array mast structural integrity is marginal under orbiter plume loading during docking or departure proximity operations. If detailed analyses assuming optimized orbiter thruster firing profiles and other operational techniques do not result in sufficient margins, design trades between mast strength improvements and orbiter thruster modifications will be performed to achieve the plume load margins. An orbiter thruster modification (reduced pulse length) to improve margins is included in the costs for Option B.

The Option B design must demonstrate compliance with the micrometeoroid and orbital debris shielding requirements. The most significant issue currently is the probability of critical failures, such as structural failure of the module or the cupola window resulting from a penetration event. Higher inclination orbits require better micrometeoroid and orbital debris protection. Current design and test activities will ensure micrometeoroid and orbital debris shield design integrity to comply with program safety requirements.

In Option B, the data management system isolates critical systems from payloads. This change is made to prevent payloads from accidentally commanding critical systems and greatly reduces the need to test and verify commands and software. The automated patch panel reduces crew involvement and increases scheduling flexibility. As in the Space Station Freedom baseline, Option B supports a safe mode of 24 hours, or more, without any contact with the ground.

Safety critical software faults include those leading to incorrect control commands or inadvertent operations that pose hazards to crew safety or station survival. Option B highly leverages the baseline program software architecture, which has not as yet demonstrated full compliance with safety requirements. Rigorous software specifications and code development, testing strategy and other controls will mitigate these risks. The program also must perform a software hazard analysis to demonstrate design compliance with program safety requirements.

Other risks inherent in Option B also have been considered. The overall schedule risk of the baseline station program was eliminated with the 19-month slip assumed for Option B first element launch. Lifetime of critical hardware, if significantly underestimated, may necessitate significant deviations from the assembly sequence baseline to allow for the unplanned maintenance. Space Shuttle flight rate reductions or curtailment longer than two years may introduce station survival concerns due to loss of critical consumables or accumulation of failures that take out critical functions. Option B is dependent on a predictable and routine access to the station for resupply purposes.

Resources Available to Users

Each discrete phase represents a performance plateau where payloads can operate indefinitely. Subsequent phases incrementally increase capabilities, allowing payload operations to grow in magnitude with each addition of volume, power and crew resources. Option B represents a core station strategy with provisions for evolution and growth as warranted by the results of early research and their application to national priorities.

Option B achieves the Power Station in two flights. At that time an orbiter and/or Spacelab could dock at the station and conduct research in life sciences, material sciences, or applied technologies. These missions could take place up to two times for Spacelab per year with duration up to 20 days, dependent on the unique requirements of each mission. In addition, payloads attached to the station truss structure could operate continuously following the orbiter's departure. These external attached payloads could be serviced, or changed out, with each orbiter visit. This scenario would allow the Power Station to sustain constant research operations in areas such as Earth observation, atmospheric monitoring, radiation and particle characterization, and materials exposure. During the Power Station phase, the station could provide up to 8 kW of power in support of both the Spacelab payloads and the external attached payloads.

The Human Tended Capability configuration adds a United States laboratory with 13 International Standard Payload Rack positions and three nonstandard payload locations. These positions could support a permanent payload presence on-orbit for basic and applied research. All positions fall within the range of one to three microgravity and maintain the 0.2 microgravity directional stability by holding a local-vertical and local-horizontal flight attitude. These conditions allow a high-quality environment for microgravity sensitive research. This provides up to 13 kW (8.5 kW with a 20-day mission) to sustain high power payload operations in areas like semiconductor and electro-optical crystal growth. A Ku-band communications system allows up to 43 Mbps of downlink telemetry, including a dedicated video channel.

The United States laboratory payload volume represents a 100 percent increase over Spacelab payload volume, thus supporting concurrent operation of life sciences, material sciences, and applied technology payloads during both crew-tended and ground-tended periods. The Human Tended Capability performance plateau adds continuous pressurized payload operations to the continuous external attached payload operations capability established by the Power Station plateau. The ability to conduct long-duration orbiter missions to the Human Tended Capability configuration remains, but no longer needs a Spacelab in the orbiter cargo bay. The United States laboratory provides all the necessary utilities, and the orbiter capability is more effectively used to deliver research samples, specimens, consumables, and payload orbital replacement units. These utilization flight missions could take place up to four times per year and be tailored to unique mission objectives and national priorities.

The International Human Tended Capability phase provides research opportunities for the international community. Both the Columbus Attached Pressurized Module and the Japanese Experiment Module are added, thus increasing total payload volume to 46 rack sites, with 30.5 allocated to United States investigators. In addition, the Japanese Experiment Module includes an Exposed Facility that provides 10 more sites for external attached payloads, with five allocated to United States investigators.

The increase in payload accommodations balances a commensurate increase in payload power from 13 to 45 kW through the addition of a second and third photovoltaic array. The buildup of the port truss also shifts the station center-of-mass toward the United States laboratory thus increasing the number of racks in the one microgravity environment. This configuration could now support concurrent, continuous research operations in all three laboratories plus external payloads on the truss and the Japanese Experiment Module and Exposed Facility during both the crew-tended and ground-tended periods. Up to four extended duration missions per year could augment the International Human Tended Capability in a similar mode to the Human Tended Capability configuration.

The Permanent Human Capability phase includes the addition of a habitation module and the necessary crew systems to sustain human life on-orbit for periods up to 90-days with assured crew return in the event of a major system failure or crew health emergency. The Permanent Human Capability configuration supports four permanent crew members in periodic duty rotations with two crew dedicated to payload operations. At this phase, scientists can continuously pursue a wide variety of research tasks with human interaction to ensure maximum productivity.

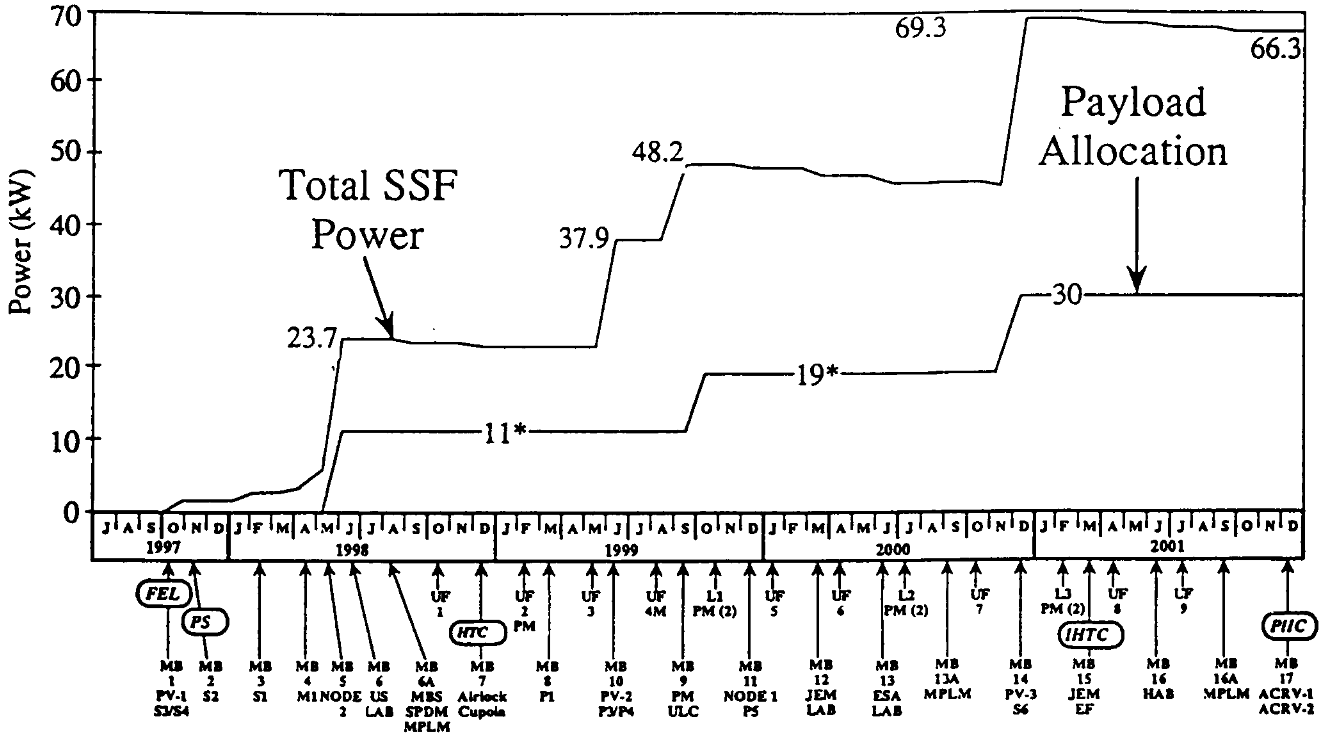
Three additional attached payload sites (two on the truss, one on the Columbus Attached Pressurized Module) bring the total to 15, covering ram, wake, zenith and nadir viewing. The 45 payload rack sites each include standardized power, data and fluid services to minimize payload integration cost and complexity. All payloads have connectivity to an automated telemetry patch panel with a total downlink bandwidth of 48 Mbps. The capability at each phase is shown in Figures 64 through 67. The microgravity environment at each phase is provided in Figures 68 through 70.

Option B can maintain the Permanent Human Capability configuration without future growth. Growth ports are available at the nodes if a dedicated volume for a large diameter life science centrifuge operation is required instead of the 1.8 meter version accommodated by the United States laboratory. Video uplink, high-definition video on-orbit, and video compression for the downlink could be accomplished through system upgrades.

Accommodation of International Partners

Option B fulfills the Intergovernmental Agreement and Memoranda of Understanding commitments to all of its International Partners. The equipment and hardware provided to the International Partners does not change. Option B retains the location and design of the International Partner elements, the resources provided to the International Partners, the interfaces between NASA and International Partner elements and the International Standard Payload Rack interface.

With Option B, the International Partner elements and operational framework remain consistent with existing United States commitments and the expectations of the partners to be meaningful, valuable components of the program. The Canadian Space Agency's robotic systems contributions remain essential to the assembly and maintenance of the station. The European Space



* Add 2 kW when unmanned

Figure 64
Payload power availability through Permanent Human Capability

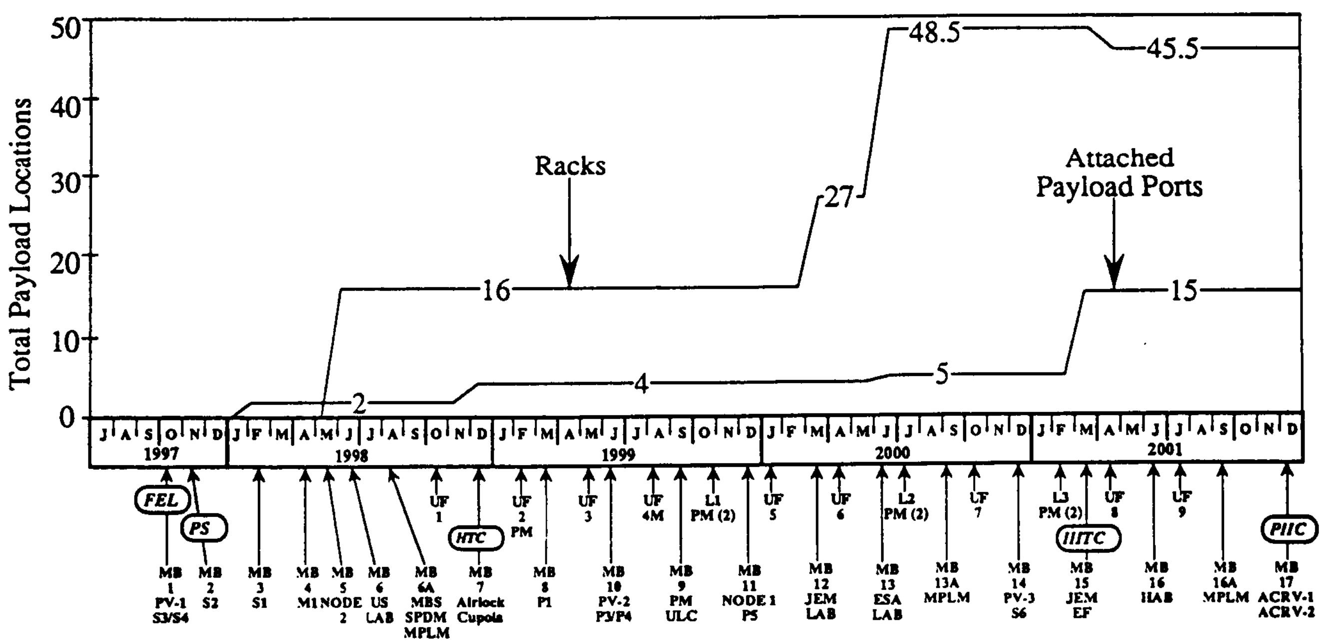


Figure 65
Total payload locations available through Permanent Human Capability

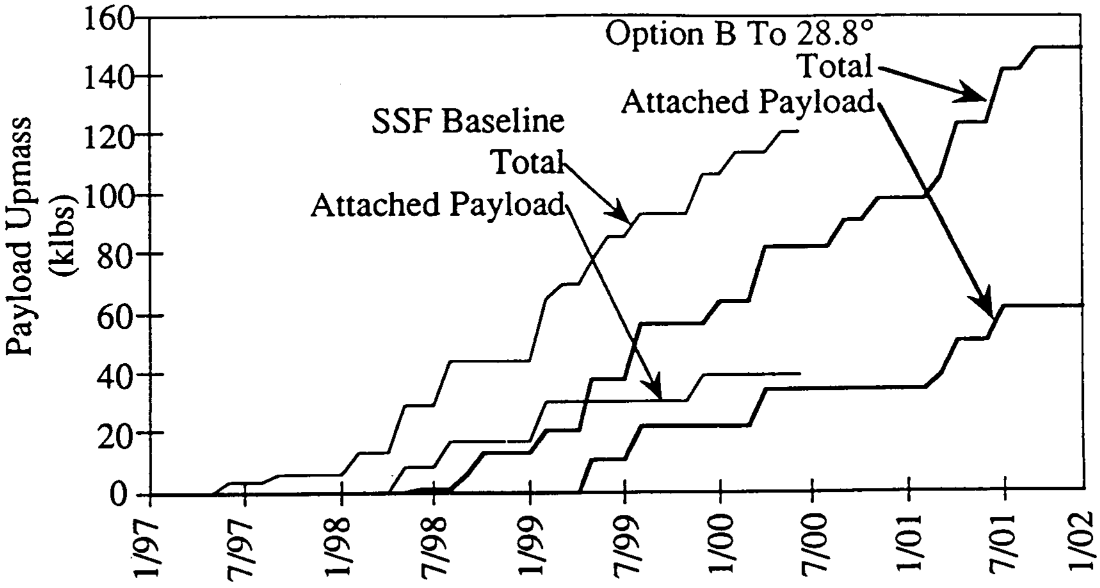


Figure 66
Payload mass delivered to orbit through Permanent Human Capability

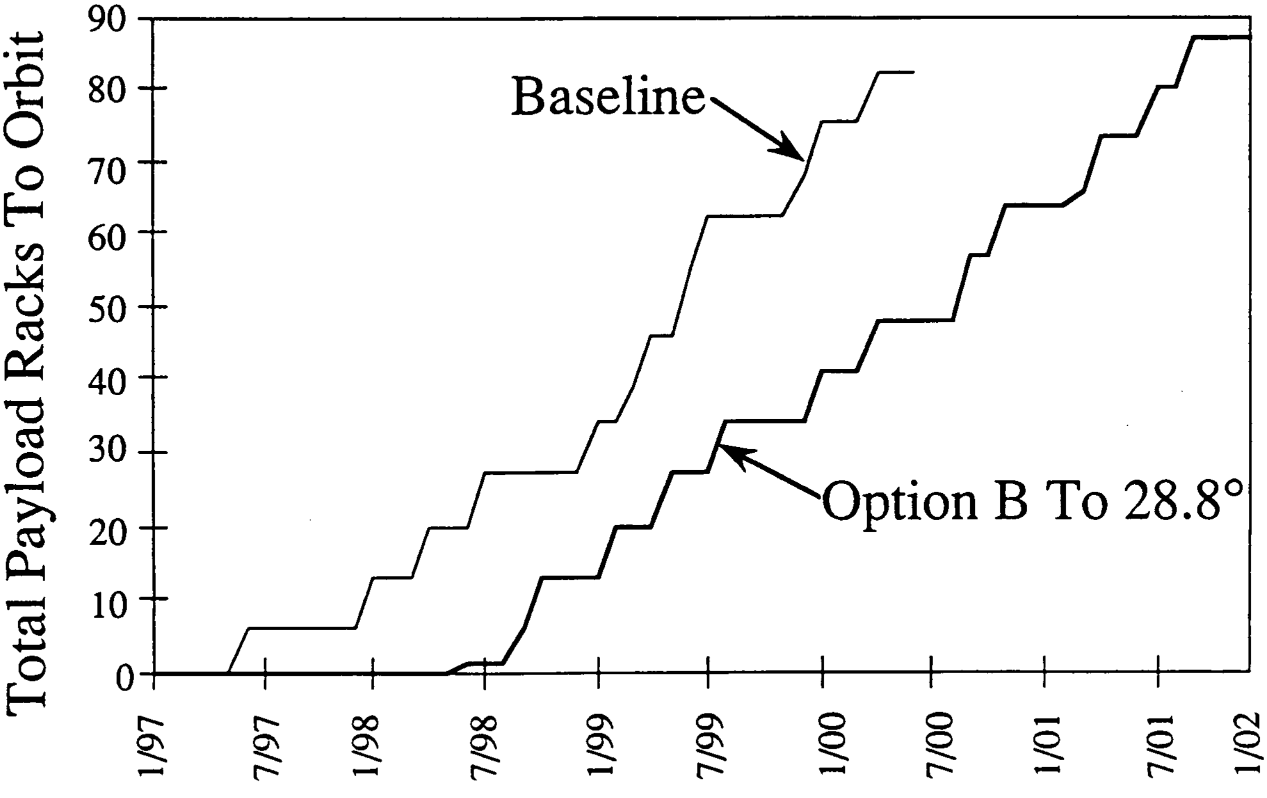


Figure 67
Payload racks delivered to orbit through Permanent Human Capability

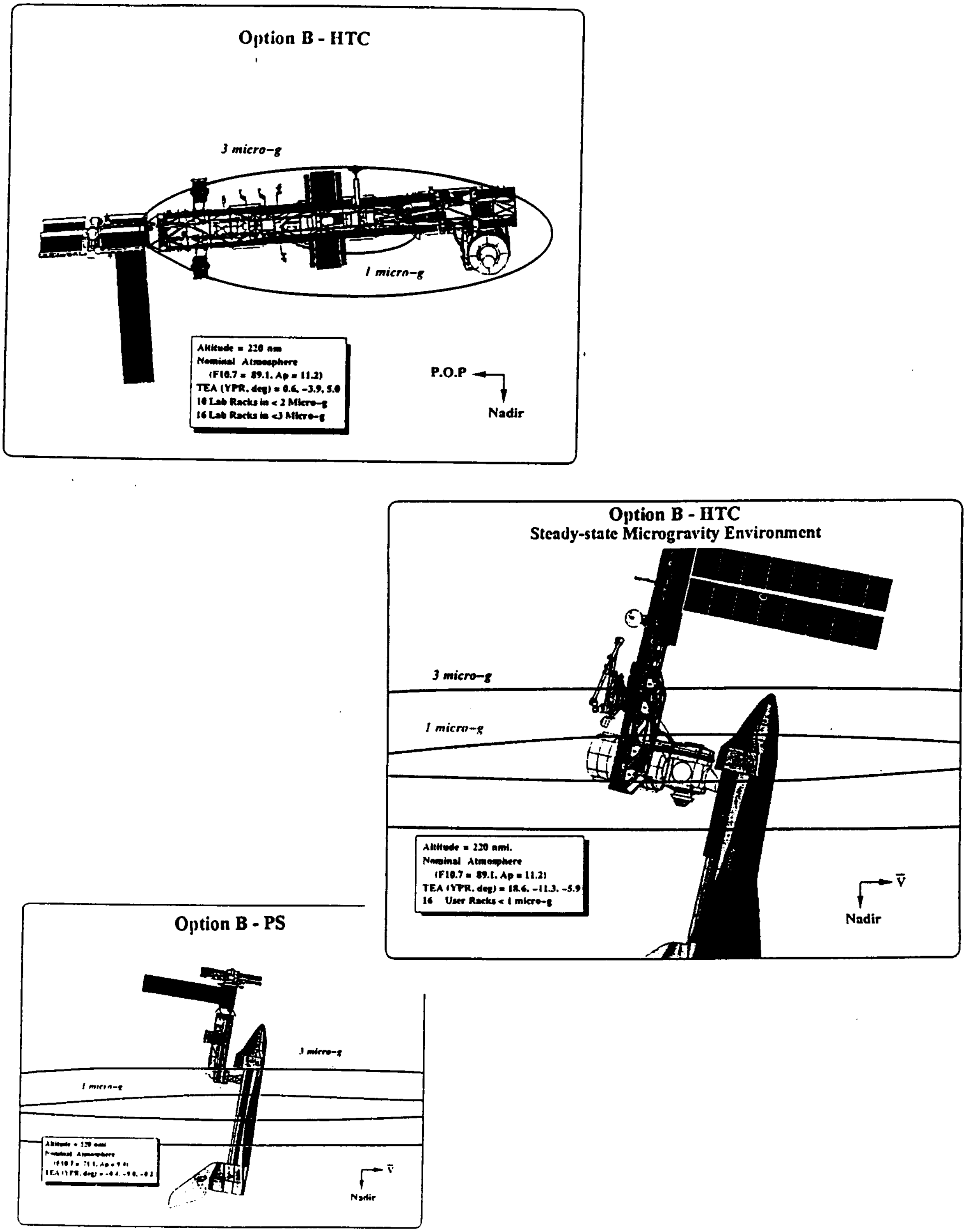
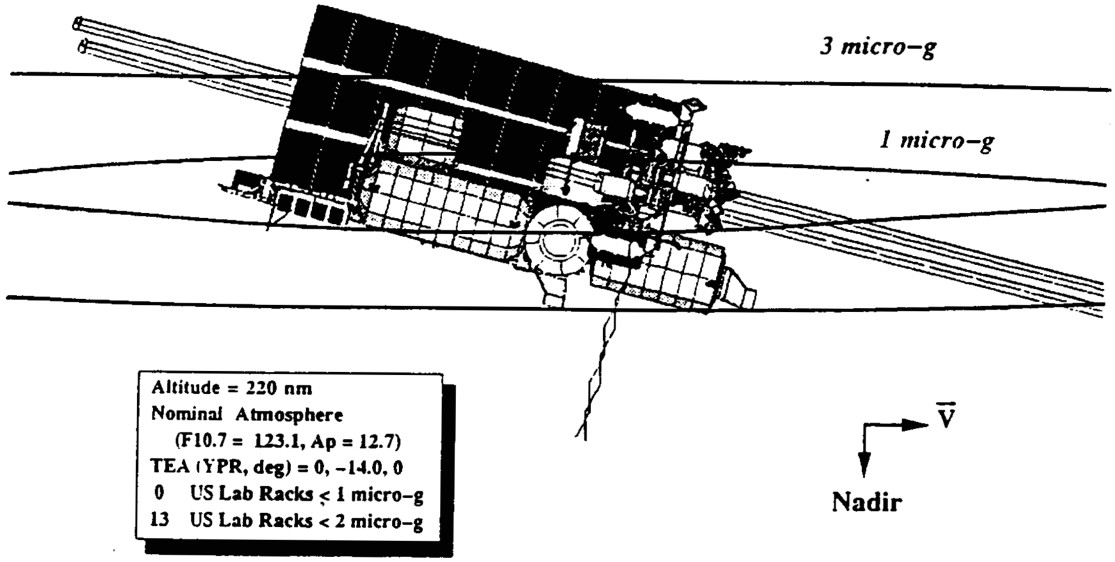


Figure 68
Option B microgravity performance for Human Tended Capability and Power Station



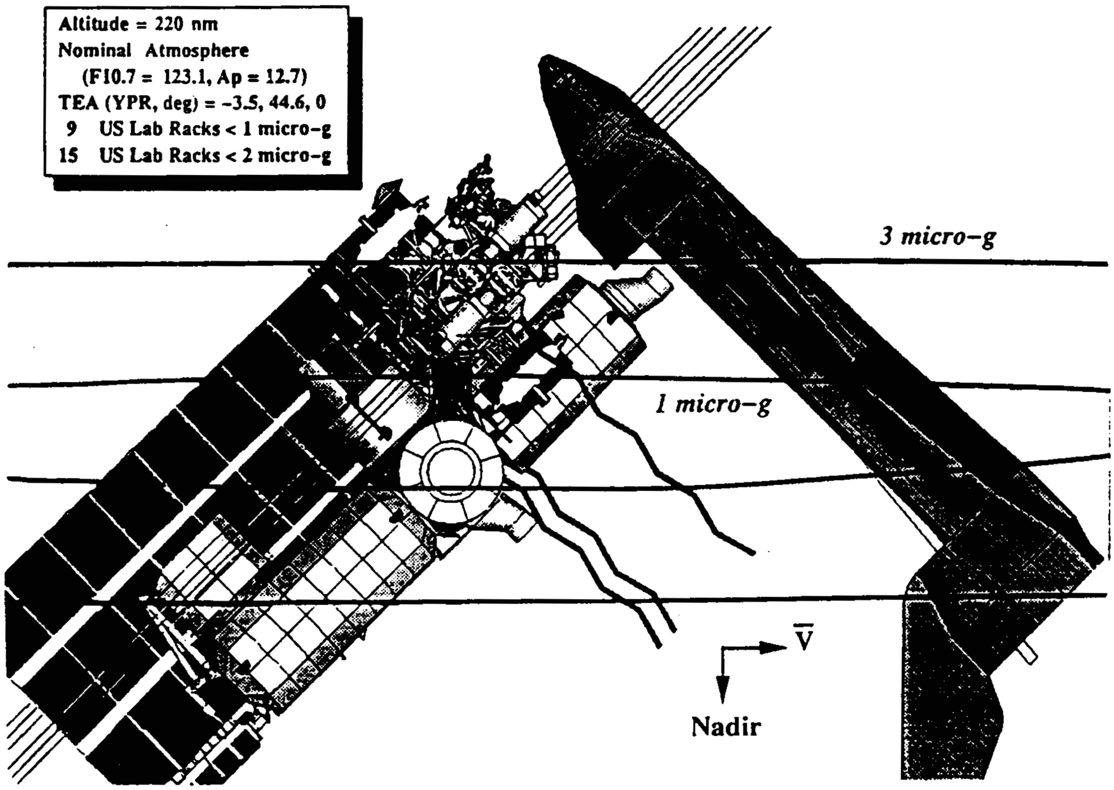
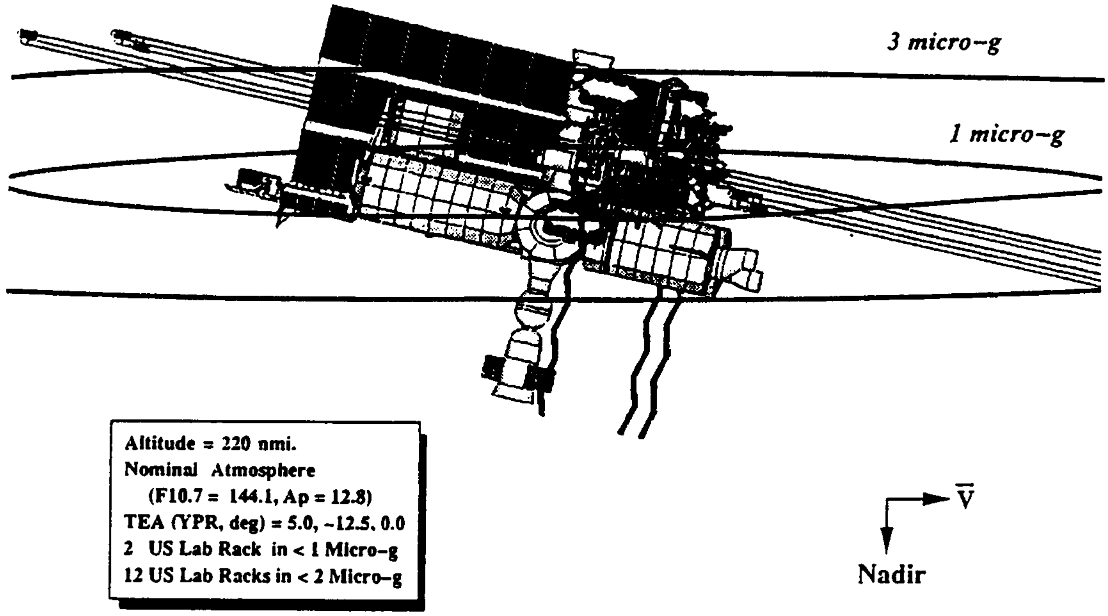


Figure 69
Option B microgravity performance for International Human Tended Capability



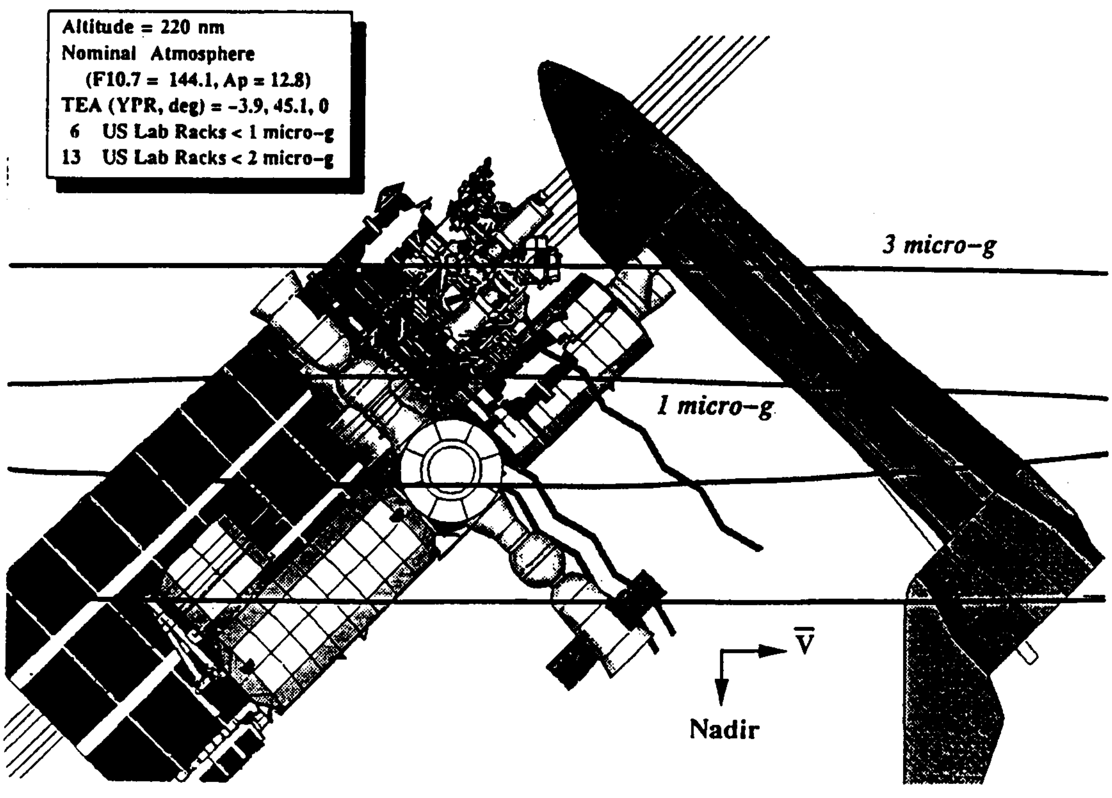


Figure 70
Option B microgravity performance for Permanent Human Capability

Agency's Columbus Attached Pressurized Module and the National Space Development Agency of Japan's Experiment Module provide more than two-thirds of the available internal user racks.

Option B maintains the previously agreed on-orbit physical interfaces and functional architecture, the international intersite deliverable agreements, and the basic multi-lateral operational structure of the station. While Option B does not provide a unique Space Station Control Center and Payload Operations Integration Center as specified in the Memoranda of Understanding, the consolidation of these functions in the existing the Mission Control Center and Payload Operations Control Center, respectively, complies with Memoranda of Understanding intent.

Option B does not utilize advanced solid rocket motors to launch the Japanese Experiment Module and the Columbus Attached Pressurized Module. This is an issue because, even with off-loading as much as possible from these modules, current module weights are in excess of Shuttle capabilities to deliver them to the required orbital inclination without the advanced solid rocket motors. Either a schedule slip, an acceleration of the advanced solid rocket motor availability, or a change of altitude for the delivery of the Space Station will be required. If weights are reduced so the Shuttle can accommodate the off-loaded modules, additional outfitting flights are still required for the National Space Development Agency and the European Space Agency to provide their laboratories with "complete basic functional outfitting" as specified in the Memoranda of Understanding.

Growth Capability

After achieving Permanent Human Capability, the assembly process may continue toward an eight person crew capability. As defined in the International Partner agreements, this milestone would include a fourth photovoltaic module to provide a total of 75 kW of power, and the habitation and crew return functions required to support an eight person crew. Other modular elements may be added to increase utilization capabilities, reduce logistics demand and provide a base for servicing free-flyers. Some of the post-Permanent Human Capability increased capability could include a second United States laboratory, nodes 3 and 4, a second cupola, a centrifuge, 300 megabits per second data downlink capability, closed loop oxygen, ultra-pure water, resisto jets and waste gas collection, and traffic management capability. These additions are largely independent of each other, and can be incorporated as utilization priorities, funding capabilities, and advanced technologies permit. None of these additions are included in the costs for Option B.

Option Specific Operations

Flight and Ground Operations

Option B makes use of the basic set of operation facilities and teams used in the baseline programs. Cost reduction related to reduced team sizes, planning templates etc. are the same as discussed in the Operations section of this report. The key flight design feature that enables these reductions is the 24-hour "safe mode" implemented in the critical flight avionics systems. Flight operations are supported by the Space Station Control Center, Payload Operation Integration Center, training center and the appropriate staffing as reduced in the cost reduction. The Space Station Processing Facility is used to ground process all flight hardware going to the Space Station. Installation is at the launch pad.

Logistics and Utilization Flights

The Space Shuttle is the baseline to deliver consumables, such as propellant, cryogenic oxygen and nitrogen, and crew supplies, as well as payloads and spare parts. Utilization flights during the assembly sequence carry both payloads and consumables. Option B provides three utilization flights per year prior to Permanent Human Capability. Figure 71 summarizes the utilization and logistics flights for Option B. As in the Space Station Freedom baseline, Option B requires five Space Shuttle flights per year after Permanent Human Capability using the advanced solid rocket motors. One or two additional flights would be required if these motors are not available.

Option B adds three logistics flights to the assembly sequence. Option B delayed Permanent Human Capability until the year 2001, adding in a ninth utilization flight. Higher drag from increased atmospheric density during the peak of

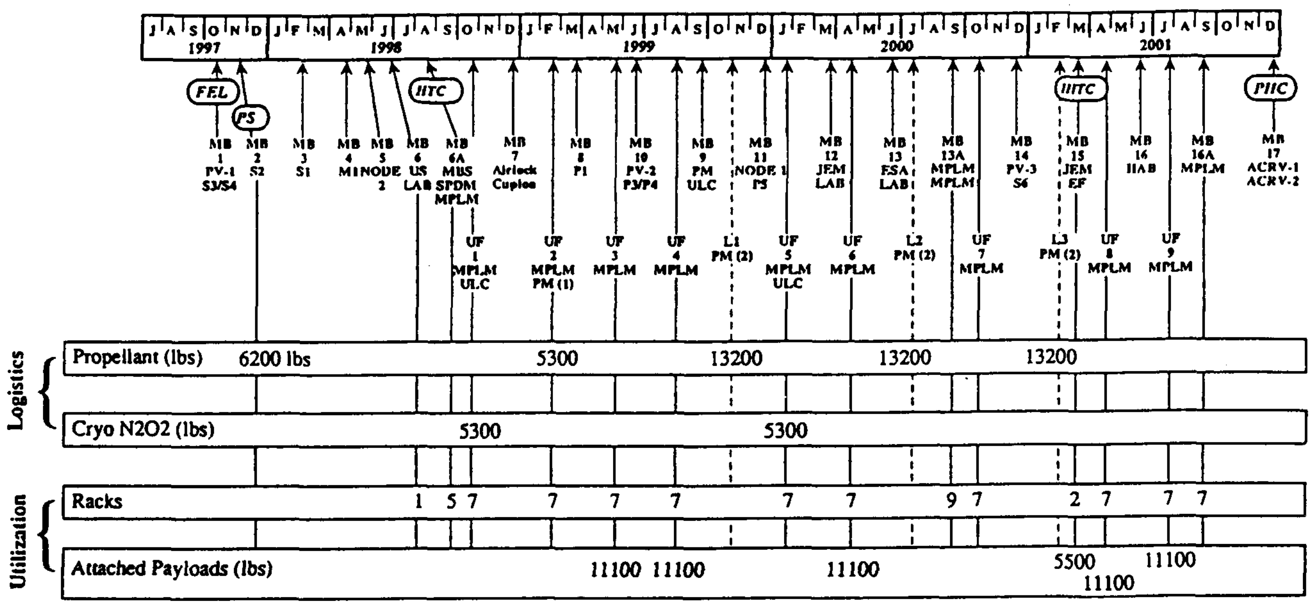


Figure 71
Option B utilization and logistiics manifest

the solar cycle results in additional propellant in 1999 and 2000 and a logistics flight, L1.

Maintenance and Spares

The maintenance strategy for Option B is the same as the Space Station Freedom baseline. The maintenance concept relies largely on the optimum design of the full robotics system: the Mobile Servicing System, including mobile transporter, to perform the external maintenance. The primary approach to on-orbit maintenance is orbital replacement unit removal and replacement. On-orbit repair will only be performed after consideration of safety, systems operations requirements, availability of resources needed, and cost. Prior to Permanent Human Capability, the orbiter crew will perform all maintenance. The availability of spares and crew time limit maintenance resources available prior to Permanent Human Capability. There is a risk that extra time may have to be spent on assembly or utilization flights for maintenance or repair of critical systems. Prioritization of maintenance tasks will consider many factors, but primarily time criticality and function. Hardware failures will not generally result in immediate maintenance actions, especially if the functions affected are low priority or extravehicular activity maintenance tasks. A sufficient backlog of tasks fill an entire extravehicular activity period, thus maximizing inefficiency.

Schedule

The 20 flight assembly sequence to 28.8 degrees begins with first element launch in October 1997 and proceeds toward Power Station and Human Tended Capability in December 1998. Option B optimizes the phasing of equipment between first element launch and Human Tended Capability for stage integration and testing at Kennedy Space Center. All of the Canadian elements are delivered to orbit in 1998. With the exception of the habitation module, almost all of the United States nonrecurring development ends by 1998. The remaining equipment required after Human Tended Capability are recurring items.

The delivery of the International Partner pressurized elements (Japanese Experiment Module and Attached Pressurized Module)

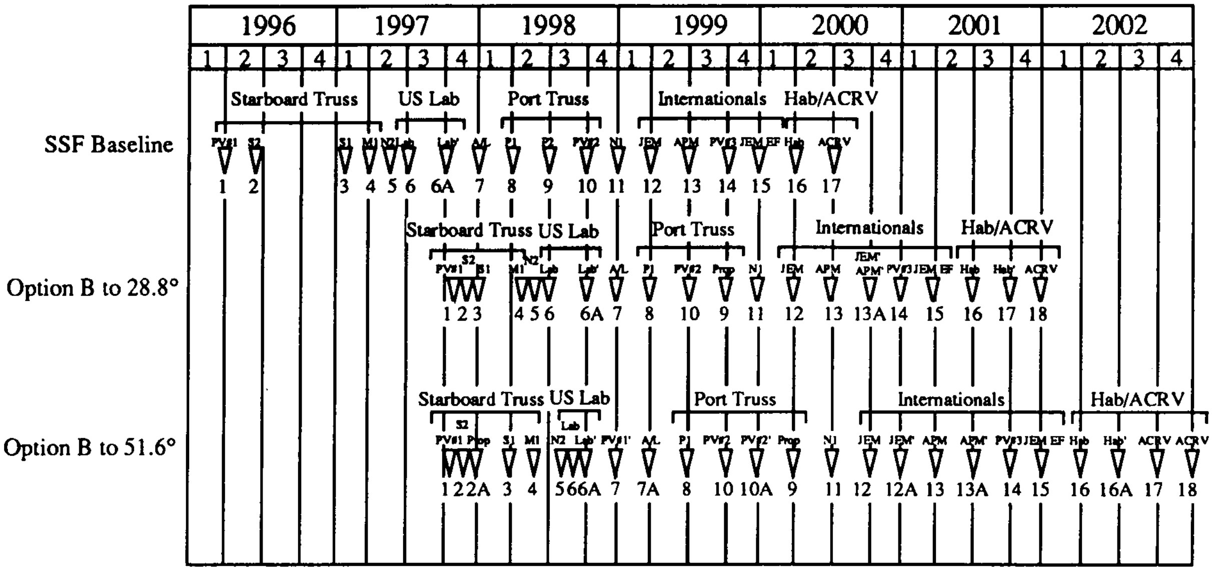


Figure 72
Space Station schedule comparisons

occurs in the year 2000. The phasing of launch dates between Human Tended Capability and Permanent Manned Capability meets a four flight per year rate to permit utilization flights at a three per year rate. International Human Tended Capability is achieved in December 2000 with the installation of the Japanese Experiment Module Exposed Facility and Experiment Logistics Module. Permanent Human Capability is achieved in December 2001. This could be accelerated somewhat by the availability of advanced solid rocket motors in December 2000. Figure 72 shows a comparison of the Option B flight schedule for both 28.8 degrees and 51.6 degrees inclination against the current Space Station Freedom baseline. Option B has considerable flexibility to 28.8 degrees but not to 51.6 degrees inclination, since first element launch is paced by the availability of the aluminum lithium external tank.

In summary, the schedule for Option B incorporates a slip from the current Space Station Freedom baseline to accommodate a significant funding decrease. The schedule for design reviews can follow the current Space Station Freedom baseline, with follow-on critical design reviews to accommodate any modifications made to systems, such as communication and tracking and data management system.

Space Station Freedom Requirements Not Incorporated

Option B Permanent Manned Capability configuration satisfies all functional requirements of the Space Station Freedom program Requirements Document and Space Station Freedom Program Definition and Requirements Document with only the following exceptions: (a) the micrometeroid environment requirements can be met with modifications once analysis is complete, and (b) the Program Definition and Requirements Document logistics flights of five per year were assumed with advanced solid rocket motors. Option B would require six without availability of the advanced solid rocket motors. Space Station Freedom requirements related to the Memoranda of Understanding and Intergovernmental Agreement with the International Partners are discussed in the section "Accommodation of Internationals." With the exception of schedules, all functional requirements of the International Partners are accomplished.

Option C

Introduction

Option C represents the most obvious departure from the Space Station Freedom baseline design. This approach simplifies on-orbit assembly issues and entails a single launch to achieve an initial operating capability. The design allows for the placement of a fully integrated 26,000-cubic-foot Space Station into low Earth orbit at an altitude of 220 nautical miles at inclinations of either 28.8 degrees or 51.6 degrees.

Option C is a derivation of many years of work at both the Johnson Space Center and the Marshall Space Flight Center. A considerable portion of the concept is based on using known and proven Space Shuttle systems and facilities that are readily available and in place. A Space Station concept similar to Option C has previously been studied at the Johnson Space Center.

The design takes advantage of much of the development work done for the Space Station Freedom program. Some 47 percent of Option C's subsystems, for example, are based on Space Station Freedom designs. Moreover, most of the Space Station Freedom components retained for this concept are already well into development.

Option C will be launched on a Space Shuttle-derived vehicle, a concept NASA first began studying in 1975. These studies matured during the 1980s into the Shuttle-C concept ("C" for cargo). The definition studies concluded in 1991 with production of a full-scale engineering development unit. Complete wind tunnel testing of ascent aerodynamics (through Mach 5.0), aerothermodynamics, and flight mechanics analysis and testing were completed on a wide range of configurations.

This large body of previous work adds a high degree of confidence to the Option C launch approach. And since it builds on Space Shuttle systems, much of the experience gained during almost 60 launches of the shuttle is directly applicable to the Option C launch phase. In fact, since the Option C design does not have wings or a vertical tail complicating the aerodynamic flow, it has the potential to be a "better flyer" than a shuttle orbiter.

Because it is based extensively on Shuttle-C and Space Shuttle data, the process and methodology for certifying Option C for launch are well understood. The Option C launch configuration falls completely within the flight envelope already identified during Shuttle-C definition studies. In the areas of ascent design and propulsion, a large amount of Space Shuttle data, tools and personnel skills are directly applicable to Option C.

Option Specific Requirements, Guidelines and Constraints

Unique guidelines for Option C are to:

1. Utilize a Space Shuttle-derived launch vehicle for the initial launch.

2. Retain all aspects of the Space Shuttle launch ascent flight control system (equipment and software).

3. Retain all features of the Space Shuttle main propulsion system.

4. Retain the structural attach locations between the single launch core system and the Space Shuttle external tank.

5. Minimize impact to Kennedy Space Center launch facilities.

6. Take maximum advantage of previous NASA and contractor studies on Space Shuttle-C and large volume, single launch space station concepts.

7. Eliminate extravehicular activity for assembly and minimize extravehicular activity for maintenance.

8. Minimize the number of components located outside the pressurized volume.

9. Take advantage of the orbiter being the Space Station's logistic vehicle:
   - Common spares
   - Infrastructure of equipment, software, facilities and operations
   - Experience base of equipment, documentation and personnel
   - Mutual sharing for component/system upgrades.

10. Minimize core overheads.

11. Maximize user capabilities.

Description of Concept

External Configuration

Option C is an integrated launch system. The launch configuration includes the single launch core station with orbiter aft fuselage, a transition section for adapting the aft fuselage geometry to the core module, and aerodynamic fairings (e.g., shroud, nose cone) mated with the standard Space Shuttle external tank and standard redesigned solid rocket boosters for the 28.8 degree orbit inclination. The interfaces between the external tank and the orbiter are used for mounting the single launch core station flight assembly to the external tank. The launch configuration is shown in Figure 73.

The aft fuselage is the standard orbiter aft fuselage, modified to remove the tail surface, the orbital maneuvering system pods and the active body flap. The standard complement of ascent avionics in the aft avionics bay is retained, as are the majority of the subsystem components of the main propulsion system, including the main engines, auxiliary power units and hydraulic systems.

The transition section is the primary structural attachment from the aft fuselage to the core module. It transfers the axial load and vehicle bending moments from the core module to the aft fuselage.

The Option C core module serves as the pressurized volume for the orbiting station and also serves as part of the launch vehicle taking all the ascent loads required to achieve orbit. The on-orbit pressurized portion is 22 feet in diameter by 64 feet long, with 10 feet unpressurized equipment bays on each end; total length is 92 feet

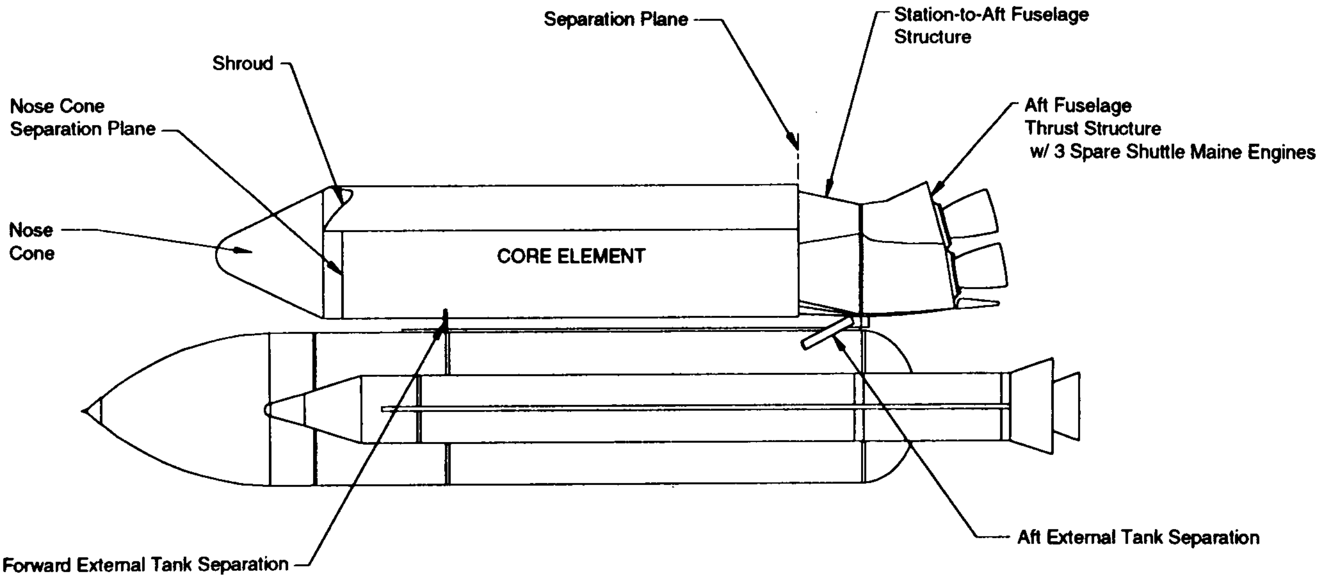


Figure 73
Option C launch configuration

with docking module extensions. Externally, the station has four nonarticulating solar array wings; body-mounted and deployed radiators; Space Shuttle and Russian Soyuz docking ports on each end; two berthing ports for the Soyuz assured crew return vehicle; five radial berthing ports to accommodate the pressurized logistics modules and International Partners; and six observation windows. The Space Station Freedom photovoltaic arrays have been redesigned to close the gap between the blankets to provide better external viewing for the Japanese Experiment Module and the Columbus Attached Pressurized Module. The common berthing mechanisms that will be used to attach these modules employ the Space Station Freedom design, with minor modification. The core module, with the Soyuz assured crew return vehicle and the Canadian Space Station Remote Manipulator System, is shown in Figure 74. The core module with the Columbus Attached Pressurized Module and the Japanese Experiment Module is shown in Figure 75.

Additional power generation capability will be obtained by adding a power module assembly to the forward end of the vehicle, as shown in Figure 76. This power module assembly, to be delivered by the Space Shuttle, will be added to the Space Station shortly after the Columbus Attached Pressurized Module and Japanese Experiment Module and will achieve Permanent Human Capability.

The primary structure of the core module is constructed of seven integrally machined cylinders attached by means of a welded ring between each. On each end is a conical end welded to the cylinder to form the pressurized volume. This primary structure has the openings required for the berthing ports and windows. It is made of 2219 aluminum alloy using standard aerospace structural design and manufacturing techniques. The major structural elements are shown in Figure 77.

Most subsystems are derived from existing Space Station Freedom or Space Shuttle components. Of Option C's 212 subsystem orbital

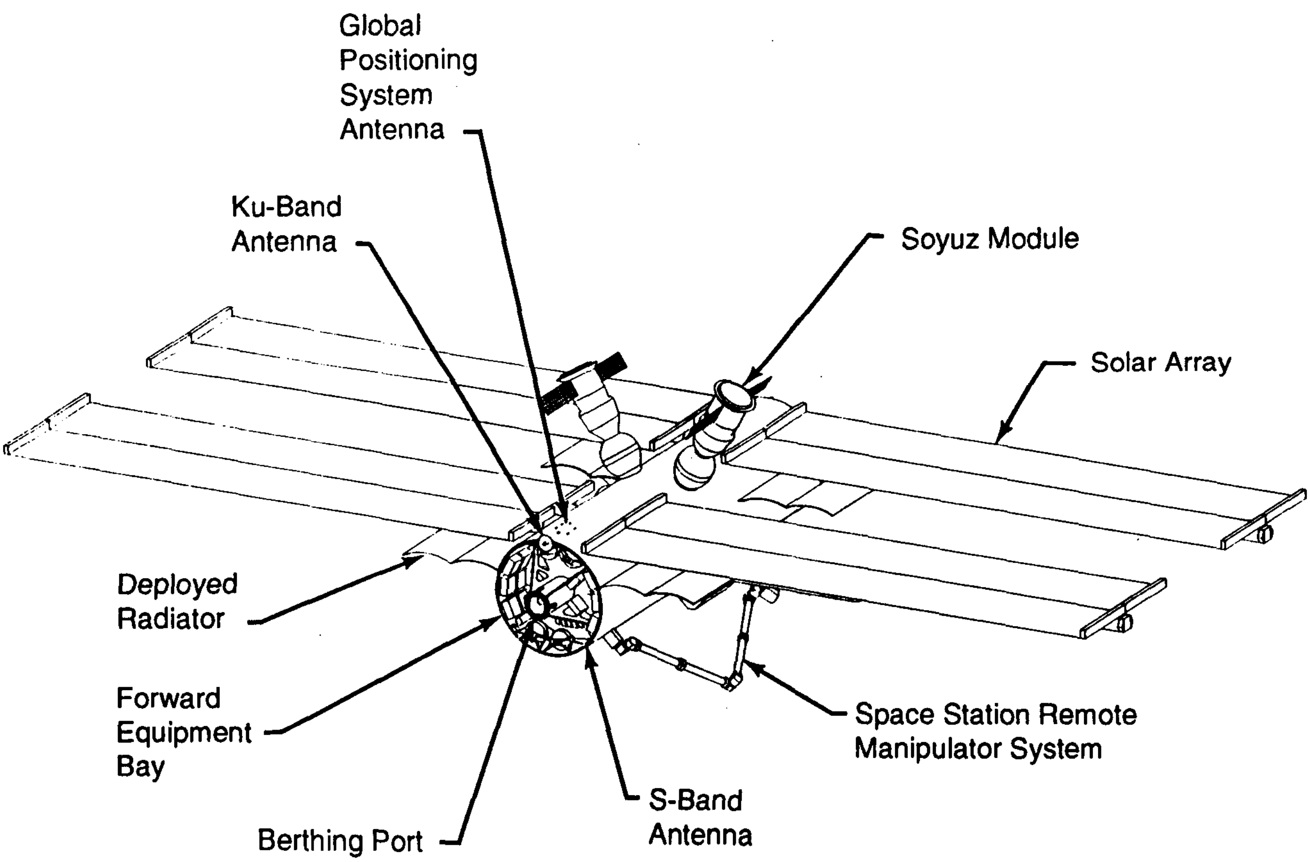


Figure 74
Option C Permanent Human Presence Capability

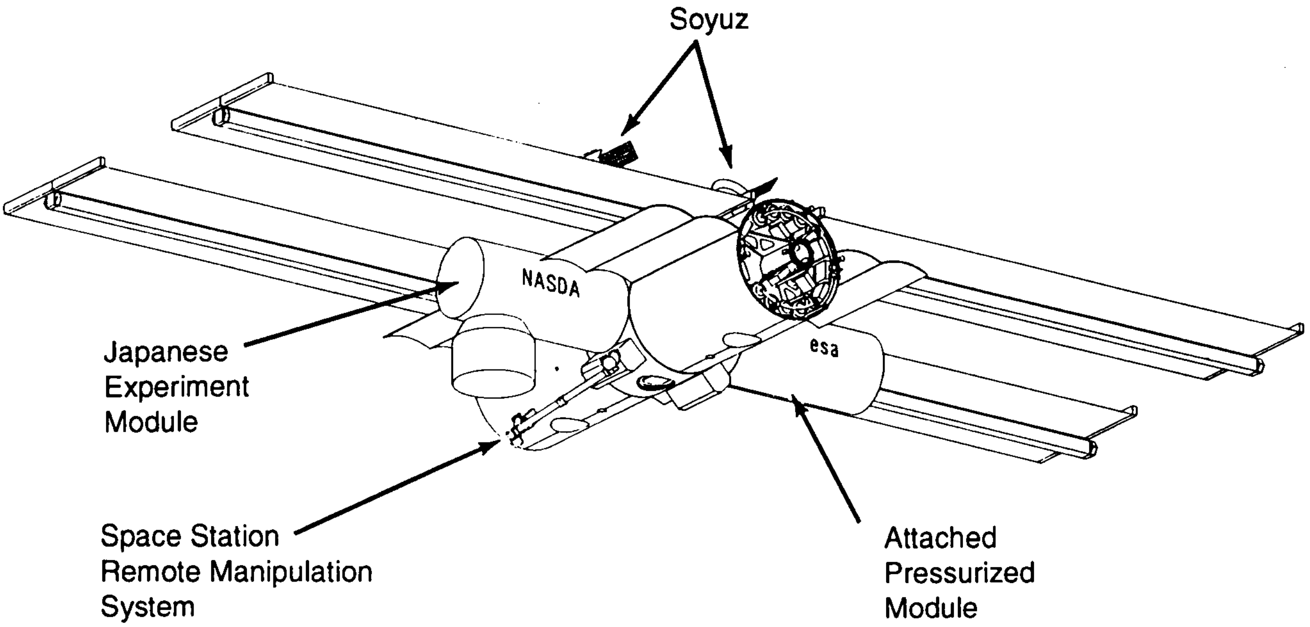


Figure 75
Option C with internationals

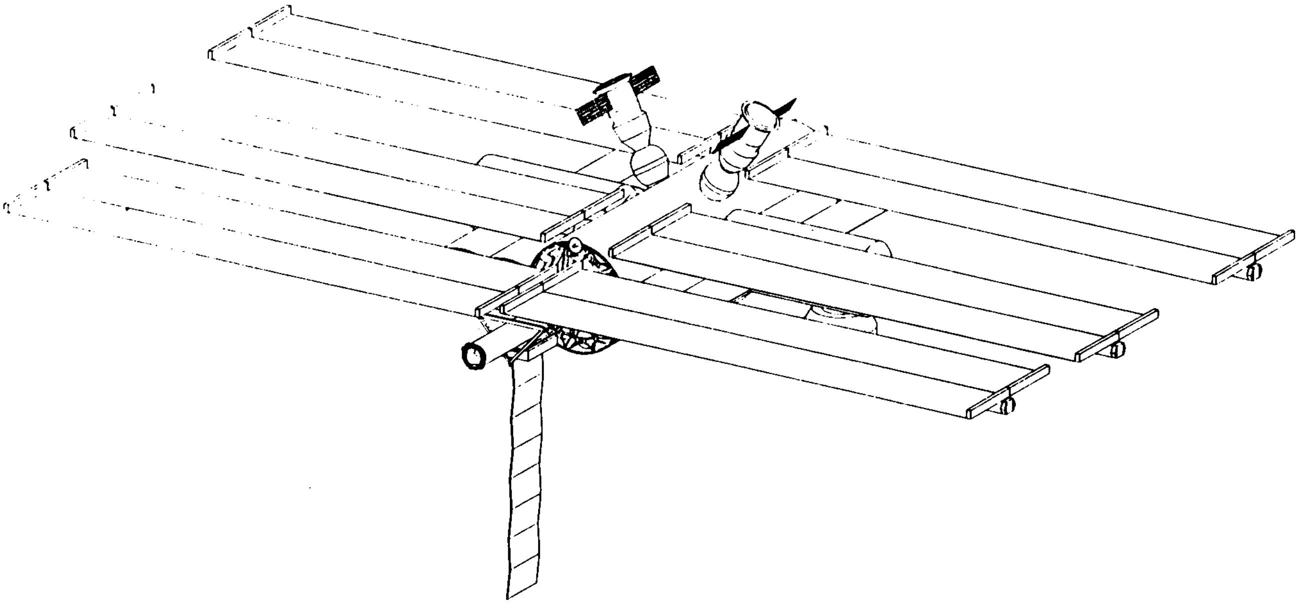


Figure 76
Option C Permanent Human Capability

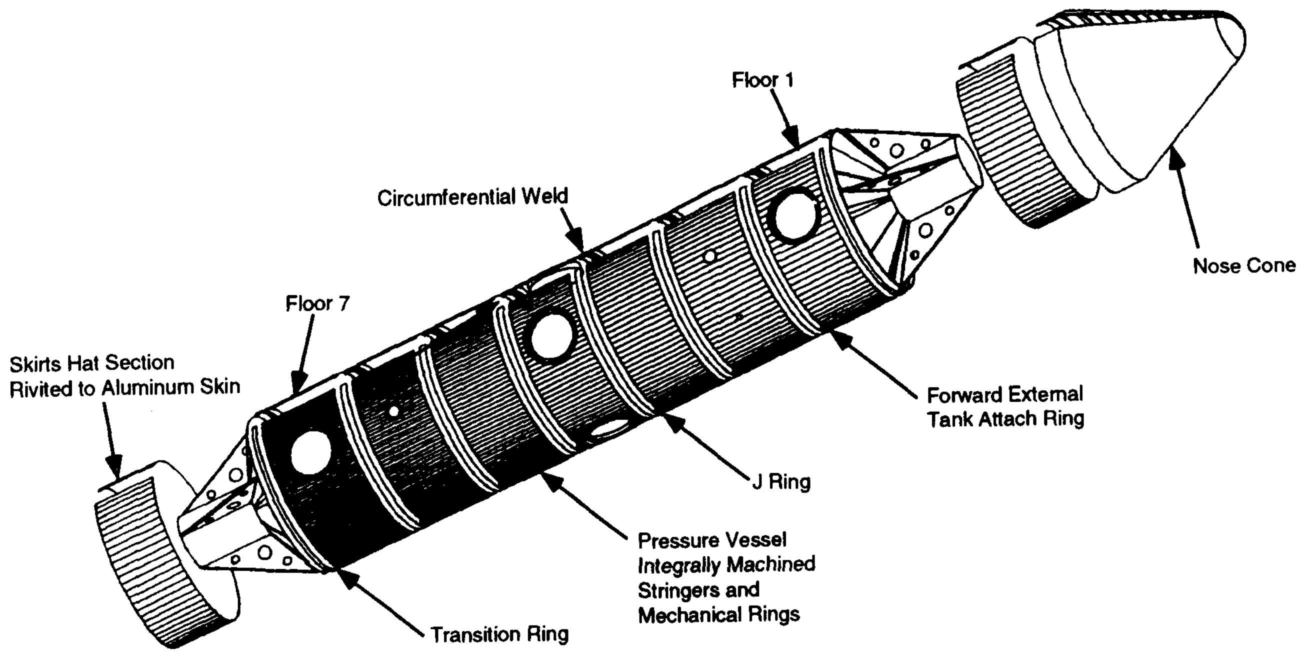


Figure 77
Option C major structural elements

replaceable units and major assemblies, 47 percent are Space Station Freedom designs, 37 percent are existing orbiter systems, and 16 percent are new designs. Those items which are new developments, however, are similar to Space Shuttle or systems developed in other NASA programs. For example, the core pressurized module is a similar design to that of the external tank; a significant amount of the existing tooling, fixtures, and ground support equipment can be used for its manufacture.

Internal Configuration

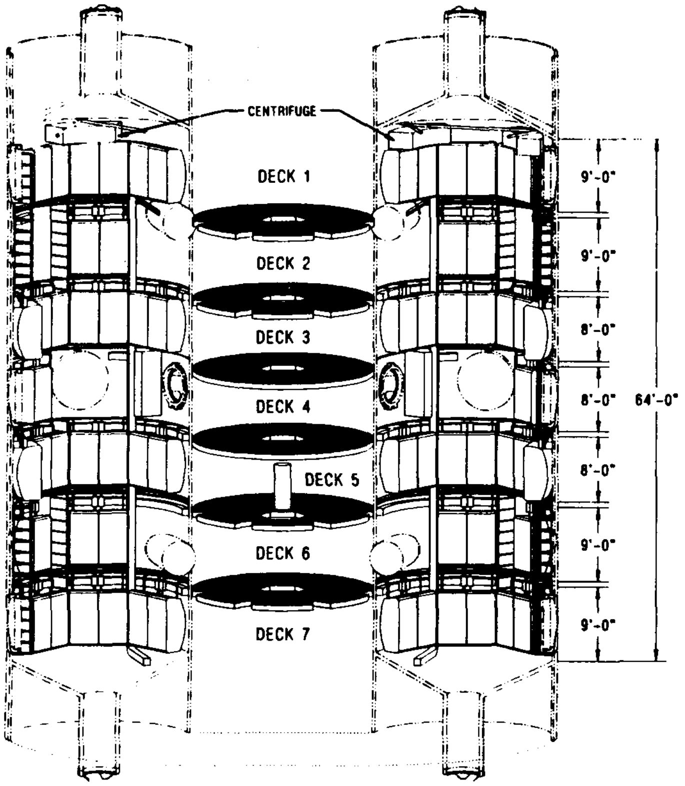
Internally, the 26,000 cubic feet of pressurized volume are divided into seven decks. The large diameter of the pressurized primary structure allows the incorporation of a six-meter centrifuge. The Space Station core module can be outfitted with 75 racks, 40 of which are available for users. Option C uses the Space Station Freedom designed International Standard Payload Racks.

The secondary structure consists of rack-to-wall attachments, floors, handholds, and rack utility supports. These are standard structural items developed during previous spacecraft programs. To reduce the weight of secondary structures, appropriate subsystem components are mounted on the module walls and end cones without racks. Utilities are routed end-to-end in cableways between the racks on the module's wall and dispersed to individual decks in circular rings above the racks. The internal configuration is shown in Figure 78. Subsystem and rack layouts are illustrated in Figures 79 and 80.

Mission Considerations

Orbital Inclination

The Option C configuration is launched without a crew to an inclination of 28.8 degrees (with an option of 51.6 degrees) and an altitude of 220 nautical miles. The 51.6 degree inclination is consistent with the intent to provide alternative access. It also provides more coverage for Earth-viewing payloads. Table 27 compares the capabilities of Option C at either inclination.



- **Deck Accommodations**

  Deck 1: Core Systems
  Deck 2: Habitation
  Deck 3: Laboratory (Medical Sciences)
  Deck 4: Berthing Ports, Crew Health Care System
  Deck 5: Laboratory (Microgravity)
  Deck 6: Laboratory
  Deck 7: Core Systems, Consumables Stowage

- **75 Rack Capability**
- **6 User Racks Provide On Initial Launch**
- **Furnace, Centrifuge and 2 Refrigerator / Freezers Provided to Users**
- **6 Earth Observation or Viewing Windows**

Figure 78
Option C internal configuration

Orbital Environment

The design reference for Option C micrometeoroid environment is for the 51.6 degree orbit, which is approximately 15 percent more severe than the environment at the 28.8 degree orbit. Option C core station probability of no penetration during the 10-year life is .955.

Flight Modes and Propellant Utilization

Option C can fly in three flight modes for optimum performance: solar inertial, which provides the maximum power; local-vertical with the X axis into the velocity vector; and local-vertical with the Y axis into the velocity vector, which provides the optimum microgravity environment. All three modes are controllable by control moment gyros. The propellant system is a backup to the control moment gyros, but no propellant is required for nominal attitude control. The guidance, navigation, and control subsystem provides an active momentum management system using gravity gradient torque to control and maintain total momentum, while controlling attitude and minimizing use of replenishable consumables. It also provides stable attitude control down to a minimum of 150 nautical miles and state vector prediction during Global Positioning Satellite nonacquisition times.

Orbit circularization, reboost and backup attitude control is performed with the bipropellant propulsion system. Following external tank and transition section separation maneuvers after launch, the propulsion system is required to provide 1,764,000 pounds-foot per second total impulse to circularize the orbit. The system requirement for reboost is 1,425,000 pounds-foot per second per year. The attitude control requirement is 75,000 pounds-foot per second per year.

Approximately 3,500 pounds of monomethylhydrazine and nitrogen tetroxide can be loaded into the Space Shuttle orbital maneuvering tanks for transfer to the Space Station during a typical rendezvous mission with no extravehicular activity required. Because the yearly propellant budget for reboost and attitude control is approximately 6,000 pounds, resupply of the Option C propellant tanks will be required up to

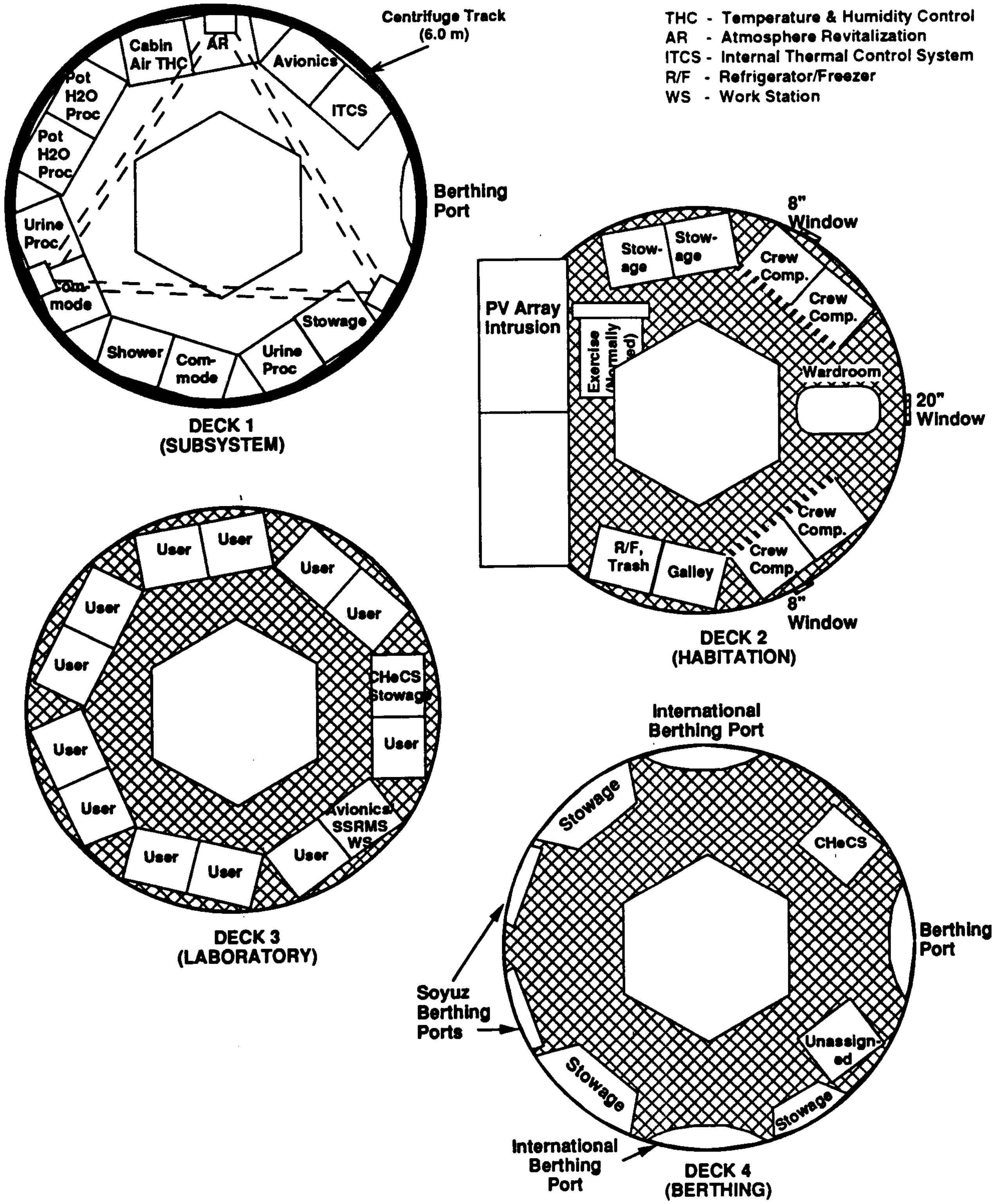


Figure 79
Option C rack layout

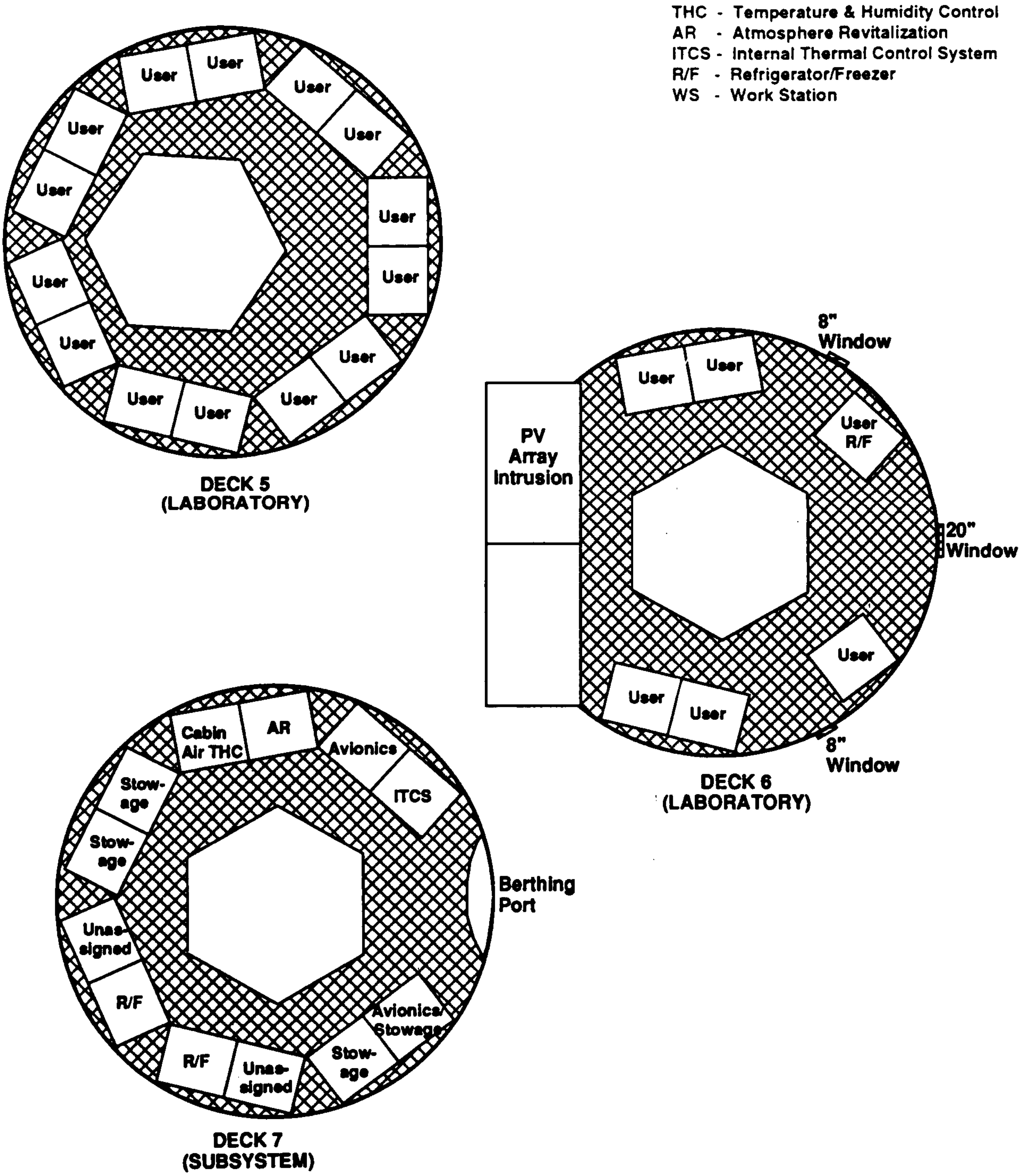


Figure 80
Option C rack layout

Table 27
Option C - single launch core station
Orbit inclination comparison

Item	51.6°	28.8°
Option C Launch to Orbit Performance	190,400 pounds	194,300 pounds
User Racks Capability Core Vehicle at Launch	6 racks	6 racks
Logistics Requirements	5 flights per year	5 flights per year
Press Logistics Carriers Required	Mini-pressurized logistics module	Mini-pressurized logistics module (stretched)
Launch Window from Kennedy Space Center	5 minutes	55 minutes
Alternate Launch Access Vehicles (Human)	Russian Launch Vehicle	None
Power Generation (Solar Inertial/Local Vertical)		
4 wings		
- Zero Beta	54.6/28.4 kW	55.4/28.7 kW
- Average shade orbit	61.3/47.3 kW	57.6/34.2 kW
6 wings		
- Zero Beta	68.4/39.1 kW	68.4/39.4 kW
- Average shade orbit	64.9/54.9 kW	62.9/46.5 kW
International Partners Delivery	Japanese Experiment Module (to be determined) and Attached Pressurized Module (Downsized)	Japanese Experiment Module and Attached Pressurized Module (off-loaded)
Soyuz Delivery	Launched from Russia (by cosmonauts)	Space Shuttle or Ariane
Earth Coverage	78 percent	48 percent

twice per year. However, when the Space Shuttle docks with the aft end of the core module, any excess Space Shuttle propellant can be transferred to the propulsion system. Sufficient propellant is kept on board so that the Space Station can survive two years without resupply.

Rendezvous Approach

Option C utilizes conventional shuttle rendezvous and approach techniques for orbiter visits. When flying in the local-vertical mode with the Space Station X-axis aligned along the v-bar, the Space Station is in the optimum attitude for orbiter approach and docking. This attitude can be held with either end of the station forward, depending on the desired docking location. This is significant because items at both ends of the vehicle require periodic maintenance and replacement.

Docking capability is further enhanced by the fact that neither the solar arrays nor the radiators articulate in a way that requires they be repositioned to permit docking. In their fixed position, edge-on to the plumes of the approaching orbiter, the solar arrays receive minimum effect from the plumes. Since the loads generated by the current orbiter primary thrusters exceed the strength capability of the array masts, Option C includes modification of the orbiter attitude control thrusters that allow maneuver and control of the orbiter during docking without imposing unacceptable loads on the arrays. The radiator panels and mechanisms are designed to accept loads produced by the attitude control system. Loads on the radiator panels also are reduced by their edge-on orientation to the plumes.

Docking loads are well within the load carrying capability of the Space Station. Using worst-case contact loads (the loads for which the docking system is designed), the solar array masts and other hardware are within their design margins.

The Option C design also maximizes the probability of the orbiter's ability to dock to the Space Station should a total loss of attitude control function occur. Option C has a gravity gradient attitude that should avoid the buildup of large rates of motion that would preclude orbiter docking.

Assembly Scenario

The Option C core module is launched into a circular 220 nautical mile orbit at an inclination of 28.8 degrees. Using the standard external tank and redesigned solid rocket booster, the payload-to-orbit capability to 28.8 degrees is 194,300 pounds (payload-to-orbit capability to 51.6 degrees is 190,400 pounds). Option C requires no on-orbit assembly to provide human presence capability. After first launch, Option C provides a functioning Space Station able to conduct selected user experiments.

After the core module is launched, pyrotechnic devices separate the launch-affiliated components, including the solid rocket boosters, shroud, external tank, nose cone, aft fuselage and transition section that are not needed for on-orbit station use. A sequence in the flight software sends commands to the motor control assemblies at the proper time to deploy the radiators.

Space Station activation occurs after orbit circularization, at which point the solar arrays and Ku-band antenna are deployed into their permanent positions, and the flight control system is activated. Space Station subsystems are initialized before transferring control to the ground. The launch sequence is shown in Figure 81.

Once on-orbit, a Space Shuttle crew can occupy the Space Station on the first visit. This early visit will serve as a shakedown mission to verify proper performance of vehicle and payload support systems, to install the remaining batteries, and to deliver one of the two required Soyuz assured crew return vehicles.

At the 28.8 degree inclination, the orbiter is used to deliver both Soyuz assured crew return vehicles, which are installed using the Space Station Remote Manipulator System. The orbiter also is used to return a Soyuz to the ground for refurbishment. (For the 51.6 degree inclination, Soyuz spacecraft are delivered by a Russian launch vehicle.) No extravehicular activity is required for the installation of the assured crew return vehicles.

The Japanese Experiment Module and European Columbus Attached Pressurized Module are brought to the Space Station by the Space Shuttle and installed using the Space Station Remote Manipulator System. The modules are berthed to common berthing mechanisms located at the lateral ports on deck four of the core module. All power and utility connections are located inside the pressurized volume and no extravehicular activity is required for assembly. The Japanese Exposed Facility and Experiment Logistics Module also are installed using the Space Station Remote Manipulator System and the Special Purpose Dexterous Manipulator.

The third photovoltaic power module assembly will be delivered by the Space Shuttle after the international modules are on-orbit. The orbiter will dock on the forward end docking port,

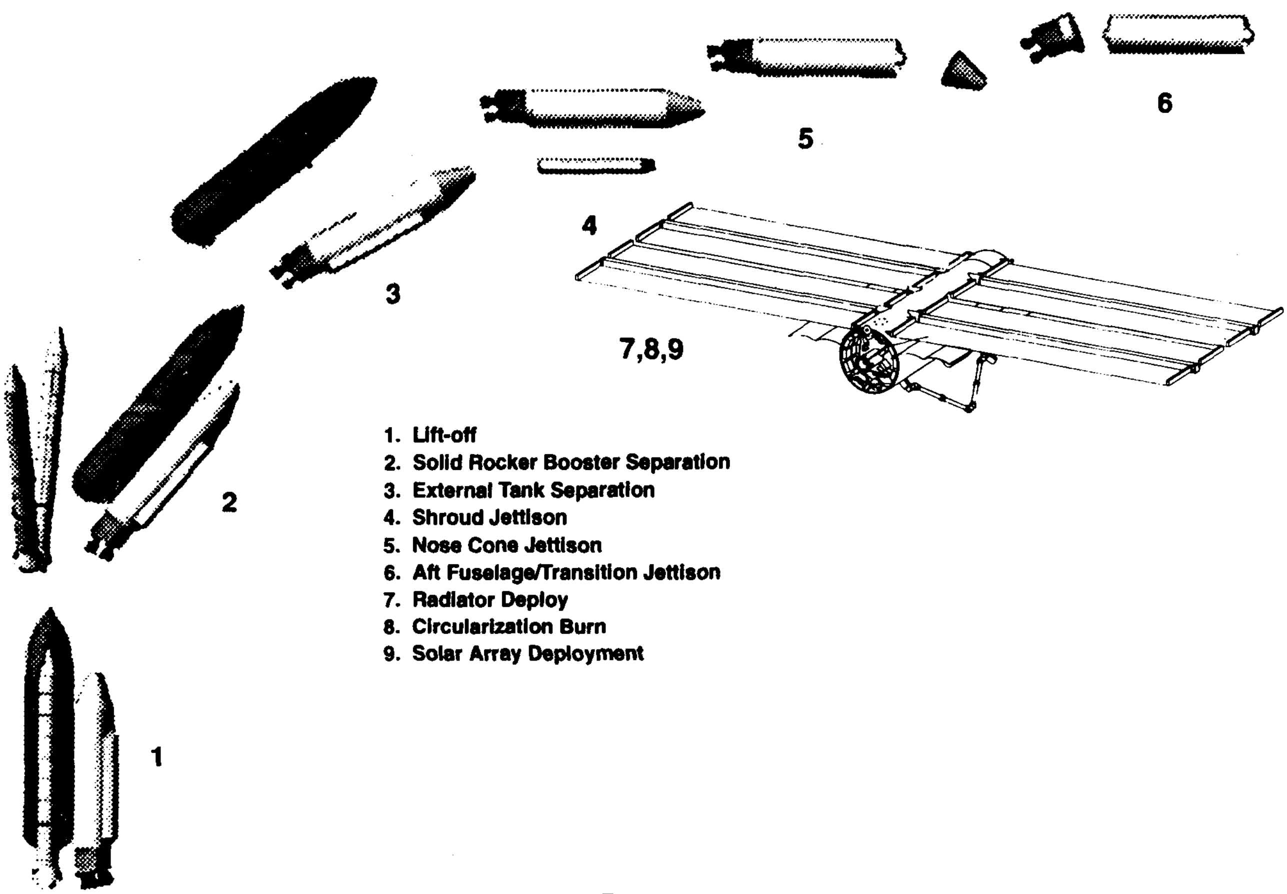


Figure 81
Launch sequence

and the Space Station Remote Manipulator System will remove the power module assembly from the orbiter payload bay. While the Space Station Remote Manipulator System is holding the power module assembly, the orbiter will undock from the forward end docking port and re-dock to the aft end docking port. The power module assembly will be permanently installed by the Space Station Remote Manipulator System. The required fluid and electrical lines will be connected by extravehicular activities.

Systems Description

Structures and Mechanisms

The mechanical systems required on Option C include the radiator deployment mechanism, orbiter and Soyuz docking ports, Soyuz berthing ports, common berthing mechanisms, attachment systems for cryogenic carriers and exterior payloads, power data grapple fixtures and the antenna deployment mechanism.

The radiator deployment mechanism deploys thermal control system radiator panels, which at launch are stowed wrapped around the exterior of the launch vehicle. The deployment mechanism is a new design but makes use of many existing orbiter radiator panel deployment and payload bay door drive system components.

Two axial ports at the forward and aft ends of the vehicle provide docking capability for both the orbiter and Russian Soyuz vehicles. Current orbiter and Mir type docking ports minus the attenuation systems will be used. The addition of the Russian radar allows for docking of unmanned vehicles. Two ports are provided to allow Soyuz to be berthed. These berthing ports are a derivative of the passive Russian docking interface.

The Option C common berthing mechanism design is based on the common berthing mechanism designed for Space Station Freedom. Automated controllers are removed, and motors and latch mechanisms are removable to reduce the number of orbital replaceable units needed.

Electrical Power System

The Option C electrical power system architecture (Figure 82) is derived from the Space Station Freedom design. The Option C power system architecture takes advantage of a shorter end-to-end system. The Option C approach allows the integrated power system to be designed, tested and verified on the ground prior to launch.

The electrical power system architecture is a 12-channel, 123 plus or minus 22 vdc system. Each of the 12 channels is composed of a single array regulator connected to one-third of a solar array wing, a single 90-cell nickel-hydrogen battery, and associated distribution hardware. Solar array power is provided to the batteries and equipment through the array regulator. Batteries are connected directly to the primary buses that feed all loads. Bus voltage therefore varies with battery state-of-charge. Power from two channels is distributed through a single module distribution unit for a total of six module distribution units. Prior to launch, six batteries and six array regulators are off-loaded. The resulting six channels are formed by closing bus crossties in the module distribution units. Reconfiguration from six to 12 channels is accom-

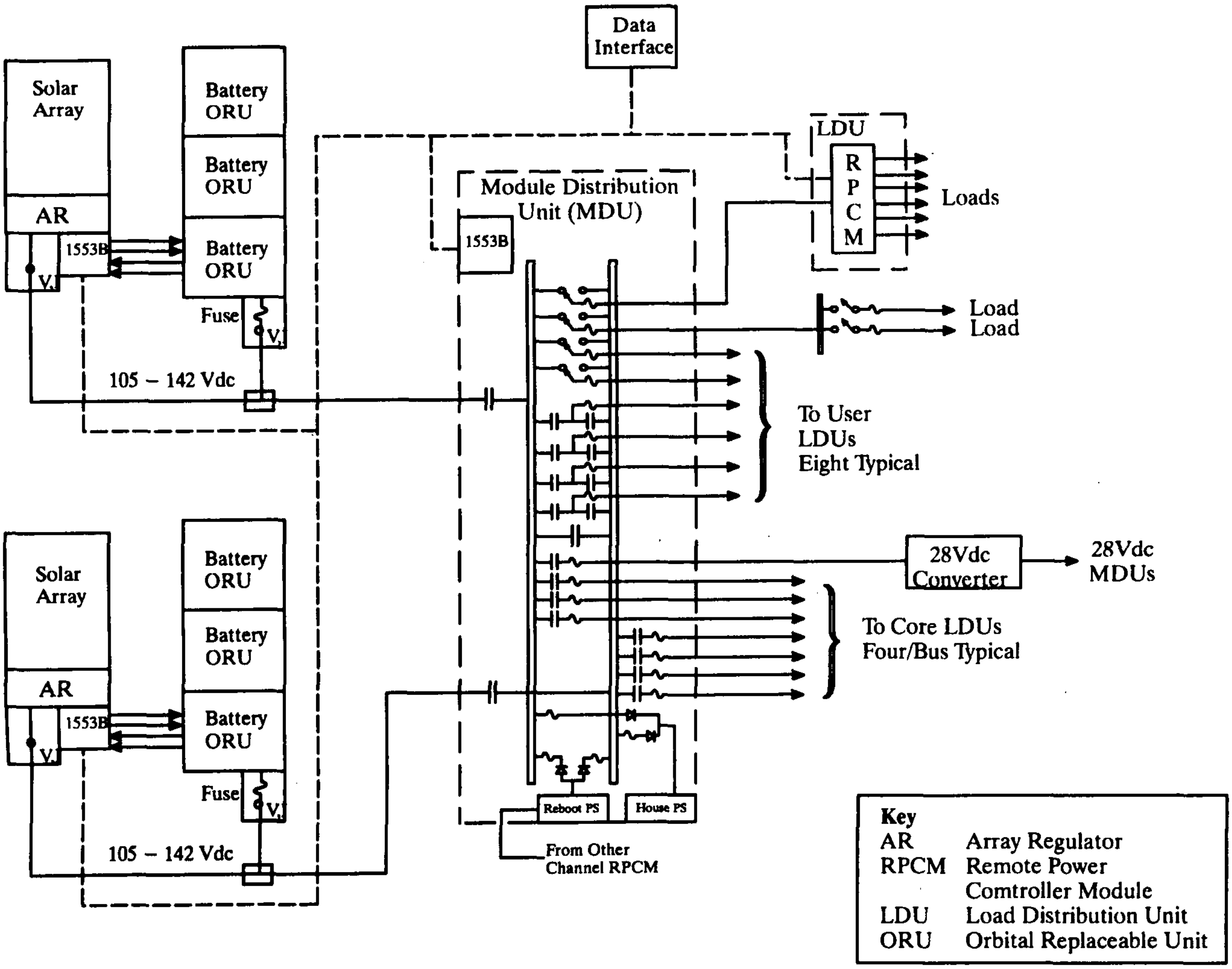


Figure 82
Electrical power system architecture

plished by opening the bus crossties when the other six batteries and array regulators are installed during the first Space Shuttle visit.

Power is distributed throughout the Space Station and to the International Partners on 120-volt buses, converted to 28-volt buses as required, as shown in Figure 83. The 120 vdc power for the Japanese Experiment Module and Columbus Attached Pressurized Module will be a regulated 120 vdc, plus or minus three vdc, as in the Space Station Freedom Program at those interfaces. The electrical power system has two levels of fault protection. Protection is provided for equipment and power faults.

A third photovoltaic power module assembly will be added to the single launch core station after the international modules are on-orbit. This power module assembly consists of two additional solar array wings, six array regulators, four batteries, thermal system, utilities and a docking tunnel system. The resulting electrical power systems architecture for the added power is shown in Figure 84.

Thermal Control System

Thermal control is provided by active and passive thermal control systems. The active system collects heat by means of coolant loops throughout the Space Station and rejects it through radiator panels mounted on the Space Station. In the passive system, thermal protection is provided by multilayer insulation, low conductance standoffs and reusable surface insulation.

The active thermal control system architecture, shown in Figure 85, consists of four external cooling loops that interface with two large internal water loops. Each active internal thermal control subsystem water loop acquires low

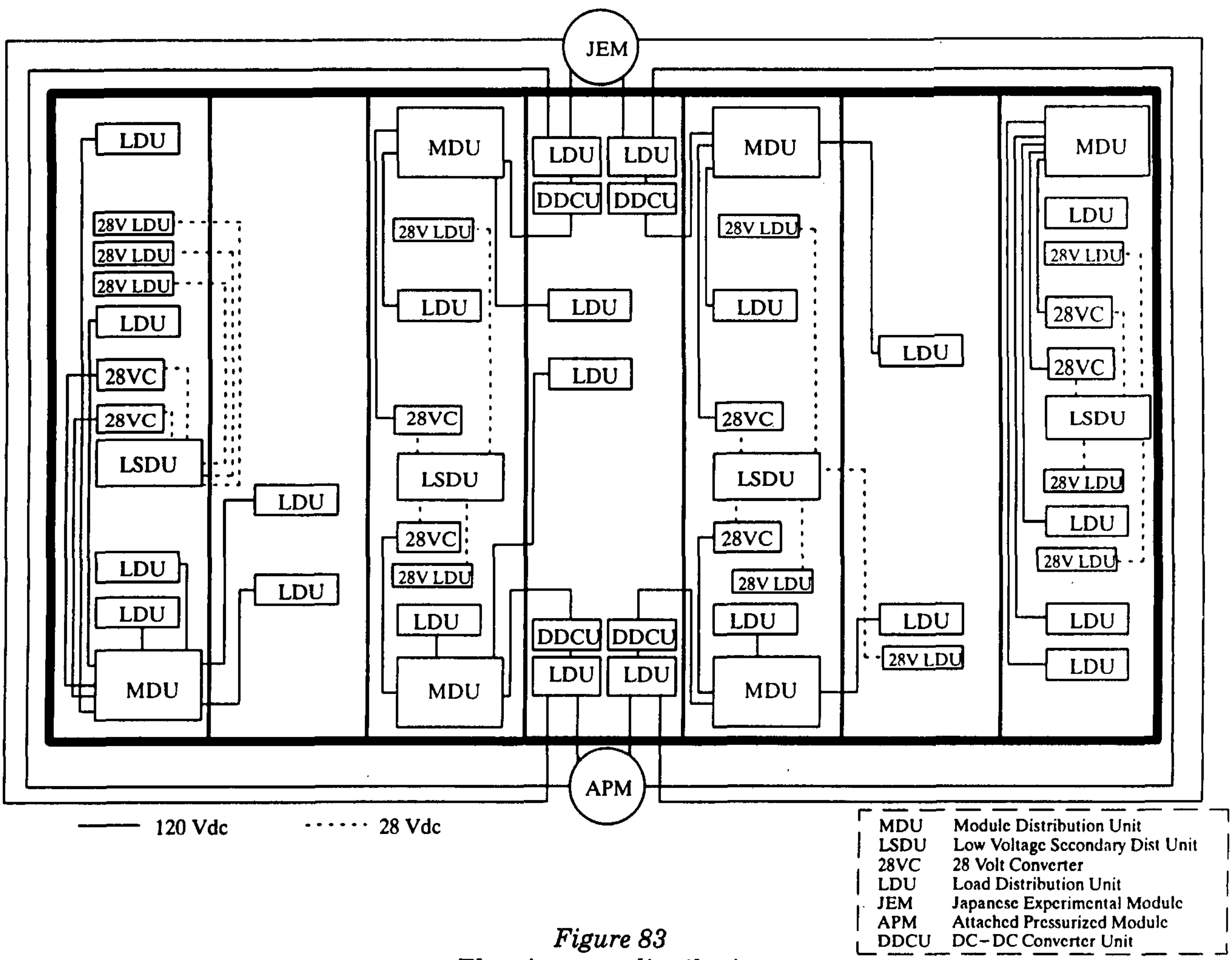


Figure 83
Electric power distribution

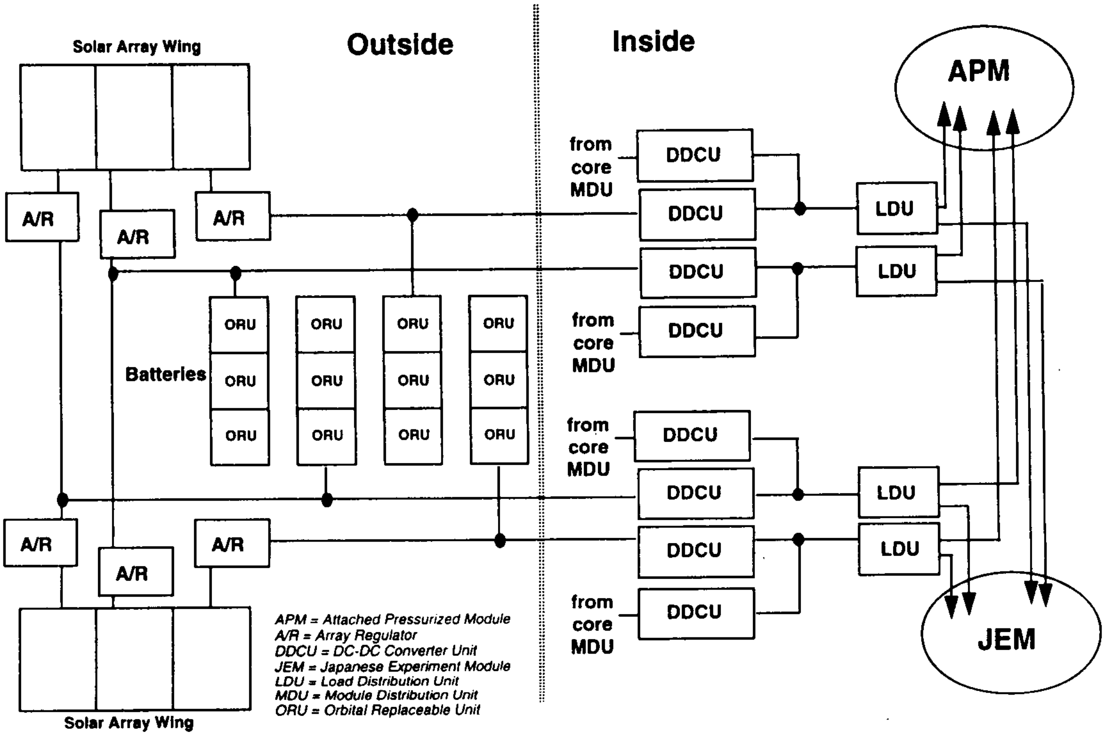
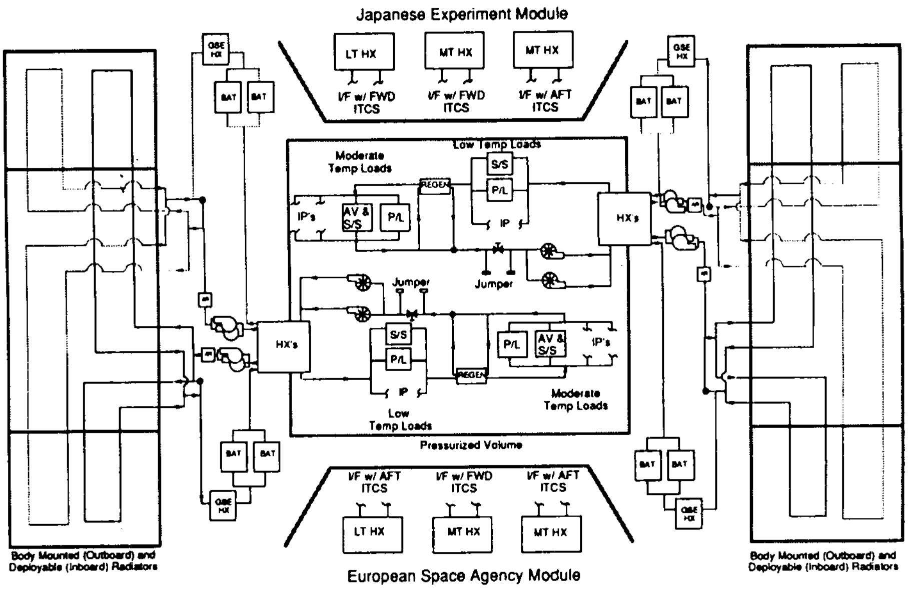


Figure 84
Electrical power system architecture for third photovoltaic wing



GSE HX	-	Ground Support Equipment Heat Exchanger	AV	-	Avionics Box
BAT	-	Battery	LTHX	-	Low Temperature Water/Heat Exchanger
AR	-	Array Regulator	MTHX	-	Moderate Temperature Water/Heat Exchanger
P/L	-	Payload	IP	-	International Partner
S/S	-	Subsystem	I/F	-	Interface
HX's	-	Heat Exchanger Set	FWD	-	Forward
Regen	-	Regenerative Heat Exchanger			

Figure 85
Thermal control architecture

temperature and moderate temperature heat loads and transfers heat through three parallel heat exchangers to two of the external thermal control loops. The external thermal control subsystem provides the thermal control to both the photovoltaic and core-cooling functions. Heat acquired from the photovoltaic batteries and core station is rejected through forward and aft sections of body-mounted and deployable radiator panels.

External Thermal Control Subsystem: Single-phase body-mounted and deployable radiators, and passive heat rejection provide 63.5 kW of heat rejection in the solar inertial attitude. The active thermal control system supports vehicle operations in local-vertical attitudes at reduced heat rejection capability (36.4 kW). The body-mounted radiators and deployable radiators run from each end skirt 34.5 feet along the core module separating the maximum radiator capacity into aft and forward zones. Two external thermal control subsystem loops share the same radiator area through dual passages. An additional heat rejection of 15 kW is provided as part of the power module growth increment.

Internal Thermal Control Subsystem: Most subsystems and all payload racks will be fitted with rack flow control assemblies. These manual valves isolate users when inactive, but are used to set constant flow to operational users. With this approach, rack flow control assemblies software can be reduced while still providing remote flow adjustment capability.

The forward internal thermal control system pump package located on deck one will provide low temperature cooling to subsystems on deck one, crew system equipment on deck two, payloads on decks three and five, temperature and humidity control cooling for the International Partners on deck four, and the user refrigerator and freezers on deck six. The forward internal thermal control system also will provide a portion of the moderate temperature cooling to subsystem and payload loads on all seven levels. The aft internal thermal control system pump package, located on deck seven, will provide low temperature cooling to refrigerator and freezers and subsystems on deck seven, and temperature and humidity control cooling for the International Partners on deck four. The aft internal thermal control system loop will service the remaining moderate temperature loads on all seven levels. International Partners are supplied low and moderate temperature cooling through water-to-water heat exchangers connected internally via quick disconnects to the International Partners' independent water loops. The International Partners interface heat exchanger is identical to the regenerative heat exchanger design.

Active Thermal Control System Maintenance: The four external thermal control system fluid loops are split into starboard and port radiator sections to create two pairs of independent radiator zones on each end. In the event of a micrometeoroid hit in a radiator tube, all of the fluid in that loop will be lost. However, each radiator zone is isolated and can be leak-checked via one of four pairs of extravehicular activity-operated quick disconnects. When the punctured radiator zone is identified, the quick disconnect pair for that zone can be disconnected, thus allowing the leak-tight portion of the loop to be reserviced.

Passive Thermal Control Subsystem: The passive thermal control system provides for thermal control of Space Station components including the Space Station Remote Manipulator System, propulsion system tanks, reboost and attitude control thrusters, propellant lines, control moment gyros and windows. The passive thermal control system also protects Space Station components from ascent heating through use of advanced flexible reusable surface insulation derived from the Space Shuttle program.

The end compartments (containing batteries, propellant tanks, lines, engines, array regulators, etc.) will be covered with a combination micrometeoroid, orbital debris and passive thermal control system end-cap to minimize heat leak.

Passive thermal control system elements for this Space Station differ significantly from those under development for the currently baselined Space Station Freedom. Current Space Station Freedom components do not have to withstand the ascent heating environment, so the addition of thermal protection system materials to the core module represents a new application of existing technology. Option C components have been moved inside or are located in unpressurized compartments at either end of the core module. Since these components are not directly exposed to the orbital environment, their passive thermal control system needs are not as great as those on the current baseline Space Station Freedom design. The Space Station Remote Manipulator System will use multilayer insulation and heaters to maintain temperatures within acceptable limits. Storage locations that will minimize make-up energy requirements are being evaluated.

Propulsion System

The Option C propulsion system will provide the required impulse for mated coast attitude control, external tank separation, orbit circularization and on-orbit reboost and backup attitude control. The external tank separation system consists of commercially available Star 6B solid rocket motors that were previously used on commercial satellites. The Space Shuttle orbital maneuvering system is used for propellant resupply. Most bipropellant components were developed in support of the Space Shuttle program or are currently being developed in support of Space Station Freedom.

Orbit circularization and reboost will use a combination of six Space Shuttle primary reaction control thrusters operating in a blowdown mode, each producing 1,100 pounds to 690 pounds of thrust. Attitude control maneuvers will be performed with vernier reaction control thrusters that are currently used on the Space Shuttle, each thruster producing 31 pounds to 20 pounds of thrust.

The Option C propulsion system is a bipropellant system that is fully integrated with the core vehicle. Command and control of the thrusters is provided by the guidance, navigation and control system. Rather than developing a resupply tanker, propellants are resupplied from the orbiter by off-loading monomethylhydrazine and nitrogen tetroxide from the Space Shuttle orbital maneuvering system into the Option C bipropellant tanks. While maintenance for the 10-year life is not anticipated to be required, specific design provisions are provided to enable contingency extravehicular activity replacement or repair of thrusters. Propellant isolation is provided to inhibit propellant leakage during removal and replacement of thrusters.

The system incorporates propellant tanks currently under development for Space Station Freedom with only minor modifications. These tanks will initially be loaded with 9,387 pounds of propellant and with 35 pounds of helium at 70 degrees Fahrenheit and 350 pounds per square inch. The maximum tank pressure is limited by the maximum thruster inlet pressure. The nominal full propellant load after resupply will be approximately 4,630 pounds at a tank pressure of 250 pounds per square inch and a tank temperature of 50 degrees Fahrenheit. The system schematic is shown in Figure 86.

The propulsion system consists of five fuel and five oxidizer tanks. The ullages of each propellant tank set are interconnected for ground servicing. Propellant for resupply of the system enters the tank through lines that bypass the propellant acquisition device. This bypass avoids the trapping of pressurant in the device. Ground servicing occurs through valves mounted so that the system can be filled with propellant external to the aft skirt in the launch configuration.

During or after orbiter docking, automated couplings will be connected between the orbiter and the Space Station to allow propellant transfer (no extravehicular activity is required). The regulated pressure of the orbital maneuvering system will push propellants into the Space Station propellant tanks.

Approximately 3,500 pounds of monomethylhydrazine and nitrogen tetroxide can be loaded into the orbital maneuvering system for transfer to the Space Station during a typical rendezvous mission. Resupply of the Option C tanks will be required approximately twice per year. However, when the Space Shuttle docks with the aft end of the Space Station, any excess Space Shuttle propellant can be transferred to the propulsion system.

Guidance, Navigation and Control System

The guidance, navigation and control system is a two-fault-tolerant system. It consists of sensors and effectors operating in conjunction with a set of applications software residing in the general purpose computer. Guidance, navigation and control operates as a single-string avionics system on-orbit, with a two-fault-tolerant capability provided by cold backup units. The system architecture is shown in Figure 87.

Sensors consist of three Global Positioning System receivers and processors (provided by the communications and tracking system) that supply position, velocity and attitude information, and three inertial sensor assemblies that provide inertial rate data.

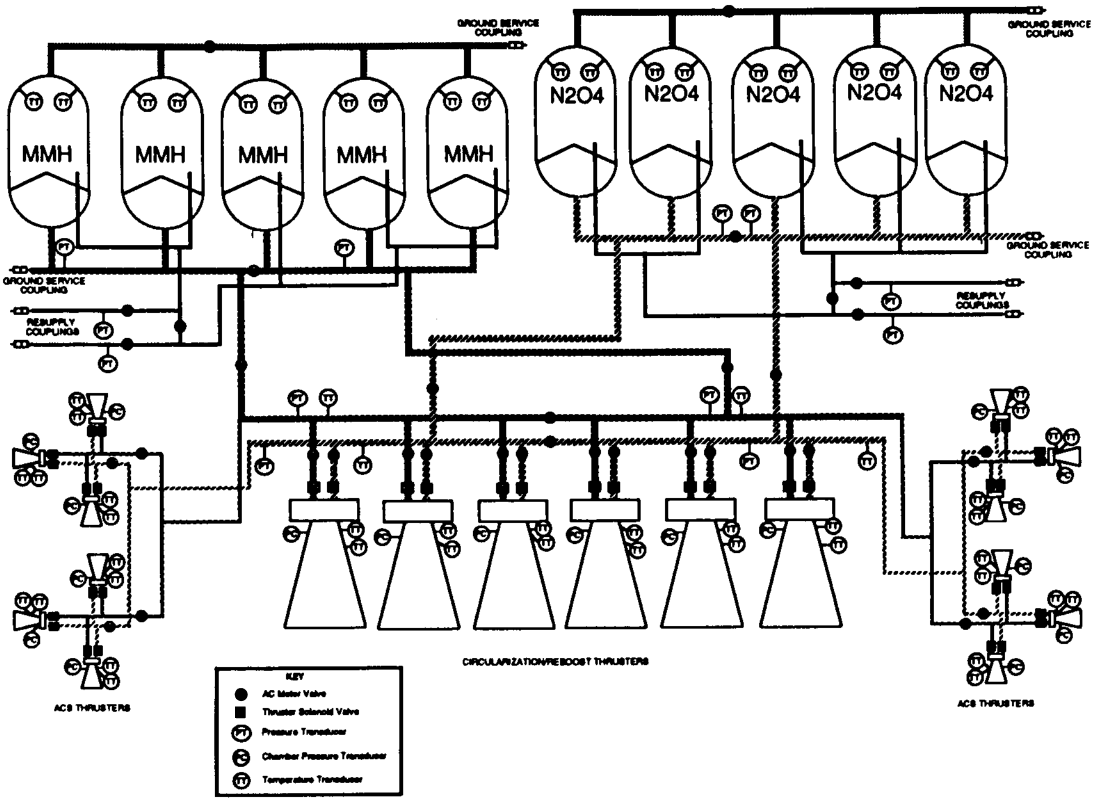


Figure 86
Propulsion system schematic

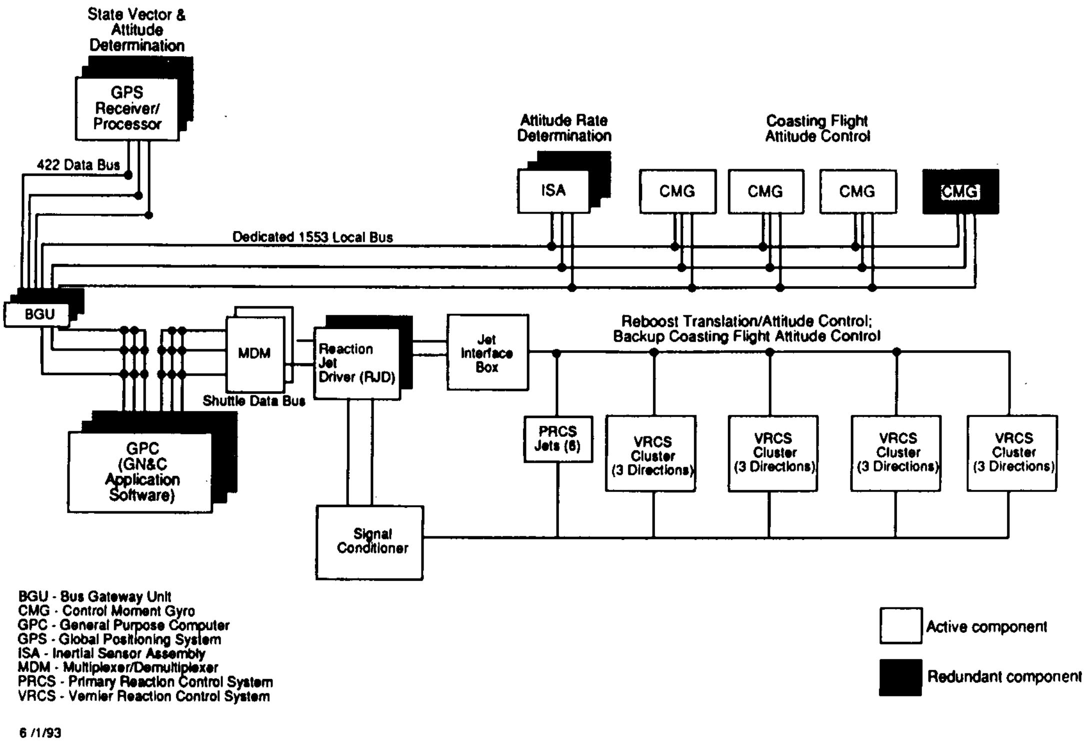


Figure 87
Guidance, navigation and control architecture

Controllers consist of four control moment gyros (of which three are normally active) and a propulsion package. The control moment gyros are mounted in the forward skirt with their respective electronics assemblies mounted inside the pressure vessel for ease of maintenance. Control moment gyros provide coasting flight attitude control through the manipulation of stored angular momentum. Primary reaction control system jets are used to perform the reboost maneuver. The vernier reaction control system is commanded, as required, to desaturate the control moment gyros and for attitude control during docking maneuvers and reboost. The orbiter reaction jet drivers will be reconfigured to accommodate the Space Station thrusters. A thruster interface unit is provided to allow redundant thruster commands to be processed.

Option C software makes maximum use of existing Space Shuttle software and will be augmented with Space Station-unique functional requirements.

Integrated Avionics and Data Management System

Option C avionics use a single integrated architecture. The integrated avionics is channeled into control domains rather than being partitioned along subsystem boundaries. The design minimizes coordination required between control domains in these ways:

- Thermal control system provides on-demand heat rejection.
- Electrical power system provides on-demand power.
- Systems manage their own resources, such as power distribution and redundancy management.
- Systems degrade in stages.

The integrated avionics based on Space Shuttle and Spacelab equipment, allowing the use of common vendors, test facilities, logistics, training, and control centers. Much of this equipment has already undergone technology upgrades and plans are in place for further upgrades to support the Space Shuttle program. Option C can take advantage of these upgrades as they become available. Most of these components also have an excellent demonstrated mean time between failure. For example, the General Purpose Computer has a demonstrated mean time between failure of approximately 50,000 hours.

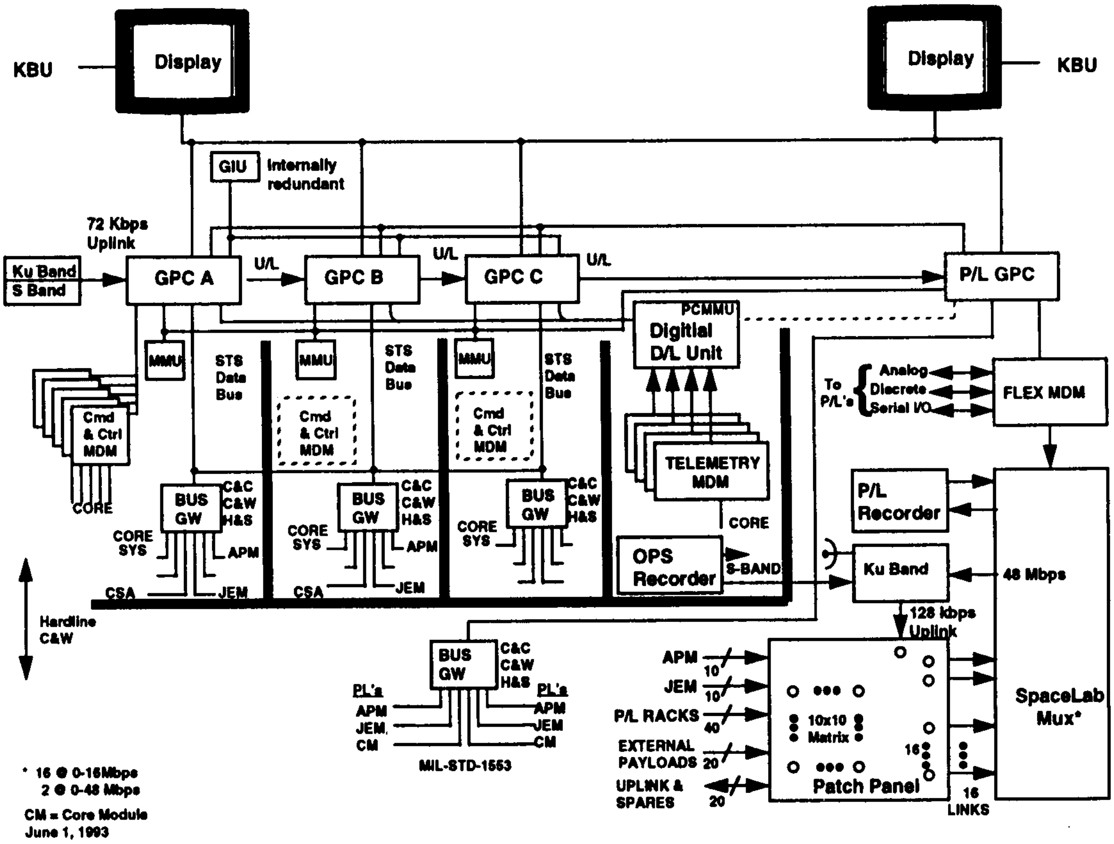
The integrated avionics provides the computational and data distribution functions, communications functions, and sensor and effector functions necessary for the Space Station to perform in the five distinct phases: ground checkout, prelaunch checkout, ascent, circularization and operation on orbit.

Prelaunch processes and application of flight rules for Option C are identical to those for the orbiter. During ground checkout, the integrated avionics are checked out and monitored. During prelaunch checkout (from the loading of the ascent software at T-20 minutes until launch), the engines and integrated avionics receive final checkout. During ascent, the integrated avionics executes the guidance, navigation and control ascent control laws and maintains telemetry downlink from launch to main engine cutoff using a parallel-redundant computer architecture.

Before firing the circularization engines, the data management system initializes a separation sequencer that jettisons the boattail and shrouds, and deploys the thermal control system radiator. During the burn, the data management system executes the guidance, navigation and control circularization control laws.

The orbital phase begins after circularization and continues through the Space Station's lifetime. In this phase, the computers are configured as a two-fault-tolerant architecture with one active computer and two inactive spares. The computational systems software executes the orbital function of communications and tracking, environmental control and life support system, electrical power system, guidance, navigation and control, and thermal control system. The integrated avionics architecture is shown in Figure 88.

The orbital phase data management system provides the computational and data distribution functions of the integrated avionics. The core computational element of the data management system consists of three Space Shuttle general purpose computers operated as a single-string centralized system for orbital operations with an autonomous two-fault-tolerant capability provided by inactive backup units. These same three general purpose computers used for the ascent and circularization are configured for multi-unit continuous operation with on-line voting and



Avionics Architecture Key

APM	-	Denotes the Interface to the European Space Agency DMS	JEM	-	Denotes the Interface to the Japanese Space Agency DMS
C&C	-	Command and Control	KBPS	-	Kilo Bits Per Second
C&W	-	Caution and Warning	KBU	-	KeyBoard Unit
CM	-	Core Module	Mbps	-	Megabit Per Second
Cmd & Cntl	-	Command and Control	MDM	-	Multiplexer/De-Multiplexer
CSA	-	Canadian Space Agency	MMU	-	Mass Memory Unit
D/L	-	Downlink	MUX	-	Multiplexer
DMS	-	Data Management System	OPS	-	Operations
GIU	-	GPC Interface Unit	PCMMU	-	Pulse Code Modulation Master Unit
GPC	-	General Purpose Computer	P/L	-	Payload
GW	-	Gateway	STS	-	refers to Space Shuttle (Space Transportation System)
H&S	-	Health and Status	SYS	-	System
I/O	-	Input/Output	U/L	-	Uplink

Figure 88
Avionics architecture (command and control and data)

fault masking. The fault tolerance is implemented with independent external monitoring devices. A general purpose computer initialization unit serves as the external monitor and provides automated switching of computers for purposes of failure management.

The general purpose computers communicate with measurement, command and control devices through distributed Space Shuttle multiplexer/demultiplexers and corresponding data signal conditioners. Space Shuttle mass memory units provide the core system with code and data retention capability. Core display and user input are incorporated with Space Shuttle systems and software from the multifunction electronics display system.

The digital downlink capability is implemented with the Space Shuttle components. These digital downlink units have selectable, predefined format collection and output. The digital downlink capability for a payload system is incorporated with the Spacelab's multiplexer function, interfacing with a Space Shuttle-derived Ku-band signal processing system. All digital uplink is received by the active general purpose computer computational string, and processing of uplink data will reside within that general purpose computer.

The payload data management system provides dedicated resources to payload users, including a Space Shuttle general purpose computer, displays and keyboards, multiplexer and demultiplexers, high-rate data downlink and recording, and general purpose computer reconfigurable table-driven payload software that provides a standard set of flexible services tailored for payloads. The capability allows onboard control and monitoring, as well as ground control and payload monitoring using a shared Space Station and dedicated uplink and downlink of payload commands and data. The payload service interfaces with payloads and is separated from the data management system for ease of reconfiguration for individual payloads. In addition, the data management system provides an interface with special user data management system equipment via a military standard 1553 data bus.

Communications and Tracking System

Option C communications and tracking system provides services to the systems and payloads as follows:

- Communications and tracking with the ground during launch and ascent via the NASA Ground Station Tracking and Data Network.
- On-orbit communications and tracking with the ground (systems and user payloads) via the NASA Tracking and Data Relay Satellite System.
- Onboard audio and video distribution.
- Tracking, attitude, and time information via the Global Positioning System satellites.

The communications and tracking architecture (Figure 89) is based on equipment that is interchangeable with Space Shuttle and Spacelab equipment. This allows the use of common vendors, test facilities, logistics, training and control centers. The communications and tracking design consists of the following subsystems: Space Shuttle S-band, Space Shuttle Ku-band, audio and video, and Global Positioning System.

Space Shuttle-compatible interfaces are provided for the onboard data system, guidance and navigation system, payload data system and user video equipment.

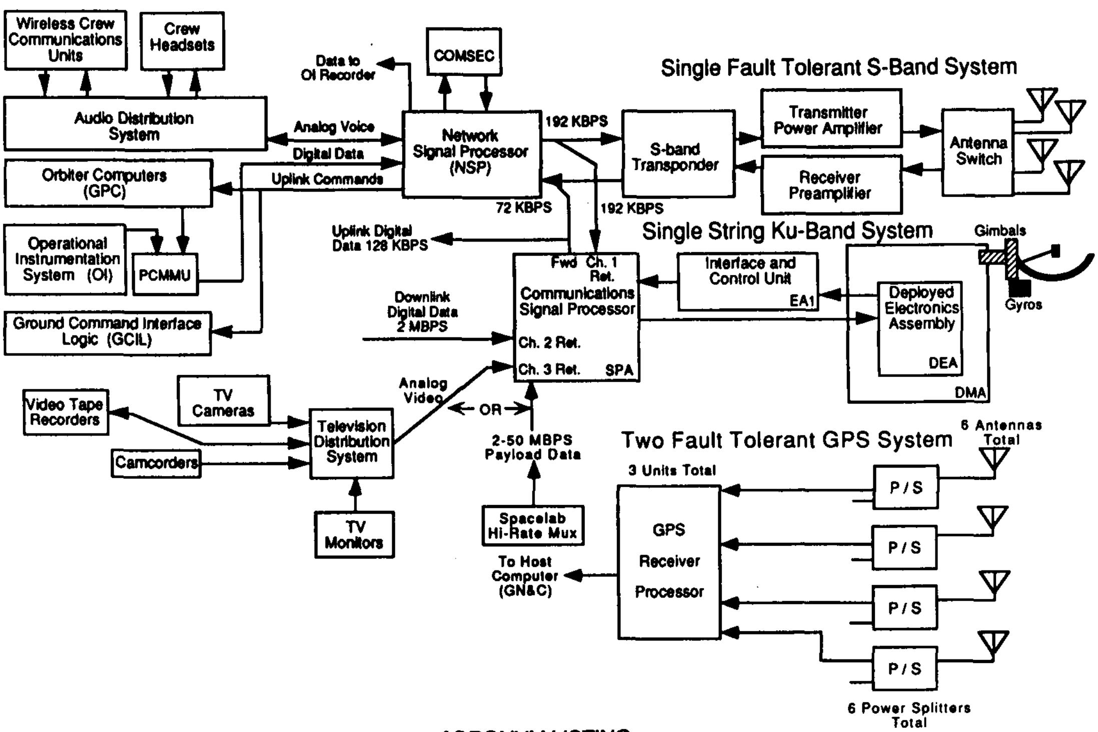
Environmental Control and Life Support System

The Option C environmental control and life support system consists of six subsystems: temperature and humidity control, fire detection and suppression, atmosphere control and supply, atmosphere revitalization, water recovery and management, and waste management.

The temperature and humidity control subsystem provides the same basic functional support as that Space Station Freedom configuration. In addition, it provides for:

- Control of cabin air temperature, humidity and ventilation rates.
- Airborne filtration for microbial and particulate control.
- Intermodule air exchange with attached elements (orbiter, logistics module, and International Partner modules) for centralized control of carbon dioxide, oxygen concentrations, trace contaminants and total pressure.
- Air circulation for fire detection and air cooling for rack-mounted equipment.
- Refrigerator and freezers for the crew and user support.

The cabin air temperature and humidity control design underwent the most dramatic design change of the environmental control and life support subsystems since it is the most configuration dependent. The temperature and humidity control design provides a single unit in decks one and seven, each capable of supporting the entire



ACRONYM LISTING

Ch.	Channel	KBPS	Kilo Bits per Second
COMSEC	Communications Security	MBPS	Mega Bits per Second
DEA	Deployed Electronics Assembly	Mux	Multiplexer
DMA	Deployed Mechanical Assembly	OI	Operational Instrumentation
EA1	Electronics Assembly 1	PCMMU	Pulse Code Modulation Measurement Unit
Fwd	Forward	P/S	Power Splitter
GN&C	Guidance, Navigation and Control	Ret	Return
GPC	General Purpose Computer	SPA	Signal Processor Assembly
GPS	Global Positioning System	TV	Television

Figure 89
Communications and tracking architecture

Space Station (excluding attached elements) in a degraded mode, using common systems from Space Station Freedom and/or the Space Shuttle and Spacelab programs.

The configuration uses a variable air volume approach with fan-powered “mixing boxes” on each deck, an approach commonly used in office buildings. This concept uses a Space Station Freedom intermodule ventilation fan and a cupola temperature control valve to draw in air from the open cabin volume or the duct supply, based on the temperature control requirements. The primary difference is that the control valve is modulated based on deck temperature rather than crew adjustment. The central temperature and humidity control fan operates at variable speed, which is controlled based on a downstream static pressure measurement.

The basic Space Station Freedom cabin air filtration design, using high efficiency particle air filters in the cabin air return ducts, was retained for this configuration. The number of filters was reduced from the Space Station Freedom Permanently Manned Capability baseline and consolidated to a common return area on deck four. The basic ventilation fan equipment was retained for air exchange with the pressurized logistics module and each International

Partner's module. For avionics air cooling, the configuration provides either a rack circulation fan assembly or an avionics air cooling assembly for rack-by-rack implementation, depending on individual rack needs.

The atmosphere control and supply subsystem provides cryogenic oxygen and nitrogen resupply, oxygen and nitrogen pressure control, total pressure monitoring, oxygen and nitrogen support for Option C subsystems, nitrogen gas for payloads, overpressure relief protection and atmosphere dump capability, and manual equalization with attached elements. Orbiter hardware is being used for the pressure regulation, positive pressure relief, and atmosphere dump functions. An interface with the active thermal control system is used to warm the cryogenic fluid before entry into the Option C pressurized environment.

The Option C oxygen and nitrogen requirements will be provided from resupply of cryogenic fluids using the baseline Space Station Freedom tanks. The Space Station Freedom baseline pressure control assembly is retained since it is readily adaptable to the planned control strategy and it contains a built-in long life, high accuracy pressure sensor.

The baseline Space Station Freedom isolation valves are retained since they are maintainable on-orbit and implement a manual override capability. The Space Station Freedom manual equalization valve provides an access port for vestibule depressurization, which is still required at the attached element interface. The Space Shuttle pneumatic pressure relief valves are used for positive pressure relief, while the Space Shuttle overboard vent assembly is used for atmosphere dumping. The vacuum exhaust system is modified to accommodate the vacuum access jumper for the attached element interface. The negative pressure relief valve is deleted because there is no abort scenario and the module will be pressurized above the maximum ambient pressure conditions anticipated at the launch site.

The atmosphere revitalization subsystem monitors and controls the level of carbon dioxide and trace contaminants in the cabin air. The orbiter regenerable carbon dioxide removal system is being used in place of the Space Station Freedom baseline four-bed molecular sieve due to power considerations. The Space Station Freedom sample distribution system and trace contaminant monitoring functions have been deleted. The Space Station Freedom trace contaminant control unit and major constituent monitor are being used with basically no hardware changes, although some operations changes and software simplifications are being made. The Space Station Freedom carbon dioxide vent has been deleted. A new, larger diameter vent (based on the orbiter design) is required to support the regenerable carbon dioxide removal system, and an interface with the active thermal control system loop is being used in place of the current Space Station Freedom and orbiter heater.

The requirement to control Space Station Freedom carbon dioxide concentration to 5.3 millimeters of mercury (0.7 percent) for the baseline Space Station Freedom program was retained. The Option C configuration has the capability to control to 0.3 percent concentration when required.

The water recovery and management subsystem recycles water to reduce the amount of water that must be supplied to the Space Station.

The Space Station Freedom potable water and urine processors are being used with only a minor design change to the potable water processor to delete the sterilizer assembly. The orbiter fuel cell water tanks are being used for additional water storage and the orbiter potable and waste water vents are being used.

The waste management subsystem provides urine collection and fecal waste management. The extended duration orbiter commode is being used in place of the modified unit planned for Space Station Freedom.

The fire detection and suppression subsystem sensor detects smoke in an enclosed volume. The primary means of fire hazard control is to prevent fires by using self-extinguishing materials and to remove power and airflow after detecting an incipient fire. The Space Station Freedom duct smoke detector design was retained for the Option C. Smoke detectors are integrated into each deck "mixing chamber" fan as well as in the deck four return leg (upstream of the high efficiency particle air filters, recessed to allow smoke detector integration). The Space Station Freedom rack fire detection system panel was retained for fire location identification in the racks.

The Space Station Freedom carbon dioxide fire extinguishers and rack suppressant distribution plumbing were retained for fire suppression. The automatic suppression system is retained for the racks. In addition, two portable extinguishers are provided on each deck.

Flight Crew Equipment Systems

The flight crew equipment subsystem provides the waste management compartment, the shower, restraints and mobility aids, the galley and wardroom, crew quarters, portable emergency provisions, portable and task lighting, stowage, decals, housekeeping and trash management, food, off-duty equipment, consumable items requiring resupply, and the configuration tracking and management. This subsystem eliminates all data management system interfaces. The Option C uses a paper flight data file rather than the Space Station Freedom baseline electronic flight data file.

The crew health care subsystem provides for routine and emergency medical care, as well as for environmental monitoring, health maintenance and crew exercise.

Crew health care system hardware occupies rack and floor locations on decks three and four. Crew exercise and associated monitoring equipment is deployed on the floor and walls of deck three. The environmental monitoring equipment, located in a rack on deck three, is used to verify the safety of the recycled water and to culture and examine surface and air samples as required. Deck three is primarily occupied by the life sciences laboratory.

Crew health care system stowed emergency medical equipment and supplies, as well as rack-mounted air and water quality analysis instruments, are located on deck four.

Extravehicular Activity System

Option C places the majority of orbital replaceable units inside the pressurized volume, which reduces the demand for extravehicular activity. If extravehicular activities are required, they are conducted from the orbiter. Extravehicular activity work sites are inside the skirts on each end of the Space Station. The Space Station Remote Manipulator system can accommodate an extravehicular activity work platform to support any extravehicular activity outside the skirt areas. The Special Purpose Dexterous Manipulator will be used to support maintenance outside the skirt areas, and in the end compartments.

The only extravehicular activity equipment manifested on Option C will be translation aids and restraints for worksites in the skirt area and under the shroud. Extravehicular activity hardware requires no power or data management system interfaces.

Automation and Robotics

The Space Station Remote Manipulator System and the Special Purpose Dexterous Manipulator are provided by the Canadian Space Agency and will have their own on-orbit control station, which will function independently of the Space Station data management system. Eight power and data grapple fixtures will be located on the exterior of the station, four along the zenith side and four along the nadir, to provide the base locations from which the Space Station Remote Manipulator System and Special Purpose Dexterous Manipulator will operate. The capability of the Space Station Remote Manipulator System to self-relocate from one power and data grapple fixture to another will allow the Space Station Remote Manipulator System to support orbiter payload bay unloading at either end of the Space Station, logistics and international berthing, cryo pallet installation, assured crew return vehicle relocation, attached payload berthing and Space Station Remote Manipulator System relocation between the nadir and the zenith sides of the Space Station.

The Special Purpose Dexterous Manipulator will be moved by the Space Station Remote Manipulator System. It can operate from the end of the Space Station Remote Manipulator System or from power and data grapple fixtures. The Special Purpose Dexterous Manipulator can accomplish dexterous tasks that require greater precision than that of which the Space Station Remote Manipulator System is capable. The Special Purpose Dexterous Manipulator will be used to perform assembly operations, external maintenance, and logistics operations, and to pre-position orbital replaceable units in support of extravehicular activity. The Special Purpose Dexterous Manipulator also will be used to service external payloads.

Manufacturing Considerations

The large pressurized structure and end skirts can be manufactured in one of several locations. The two most promising sites are the external tank manufacturing facility at Michoud or the facilities at the Marshall Space Flight Center. For costing purposes, it was assumed to be manufactured at Michoud. Two flight structures will be manufactured. The first unit will be shipped to Johnson Space Center and used initially as a pathfinder for installing the secondary structure, electrical wiring, plumbing, and representative subsystems. Later it will be used as an engineering test article and crew trainer. The second flight structure will be delivered to Kennedy Space Center where it will be outfitted, checked out and mated with the other flight elements. The first structure will be used as a back-up flight article to the primary flight article.

Test and Verification

Option C requirements will be updated at a Program Requirements Review shortly before contract Authority to Proceed. The program requirements, including integrated system performance, payload resources allocations, system operability, and product assurance, will be updated. The requirements and specifications for individual subsystems will be likewise updated for System Requirements Reviews. Based on these updated requirements sets, systems verification plans and program verification plans will be reconstituted along with plans for integration and checkout at Kennedy Space Center. The updated plans will include verification responsibilities, approaches and management plans.

Thirty-seven percent of the selected components are already flight-certified from the Space Shuttle program. Follow-on analysis and testing will be conducted to ensure that the components can tolerate worst-case flight environments. System components that are of a new design for Option C will be subjected to engineering evaluation testing and certification.

Subsystem designs are implemented with available hardware and software to verify the basic system performance. Extensive use is made of existing test-beds for system development and certification testing. Systems including the environmental control and life support system, thermal control, propulsion and electrical power systems will rely on early system development testing and analysis to determine final system configuration to achieve best performance. Final system designs within and between systems, and completed system safety analyses, will determine the final verification requirements.

The data management system will use existing system development facilities of the Space Shuttle Processing Facility and Software Development Facility and the Johnson Space Center Avionics Engineering Laboratory for engineering evaluation and flight certification testing. Data management system development testing will concentrate on the differences from the Space Shuttle system.

System operations concepts will be verified using mockups and trainers, which simulate the layouts on individual decks of the station. Individual deck mockups will aid in the development of systems with heavy crew interaction such as crew equipment, crew health care, and payloads.

Robotics and extravehicular activity operations will be simulated, analyzed, and tested using existing computer models and Weightless Environment Training Facility mockups.

Individual subsystems and the integrated vehicle performance rely on analysis for those conditions that cannot be adequately tested on Earth. Standard analysis tools for the engineering disciplines (structures, thermal, communications coverage) will be used as required to verify subsystems performance. Verified analysis tools developed for the Space Shuttle will be used. These include ascent flight control and stability, component separation and entry footprint, trajectory profile and orbit insertion. Other analytical tools from the Space Station Freedom program include those for guidance, navigation, and control (rigid and flex body stability, rendezvous and proximity operations, guidance, navigation and control system performance, and transient response).

Other analytical tools are used to validate both internal and external environments. Analysis results will play a significant role in the definition of loads and interfaces for the Japanese Experiment Module and Columbus Attached Pressurized Module.

Results from the verification analyses will be available early in the system design process and will be refined and iterated with mature design information at system and program design reviews.

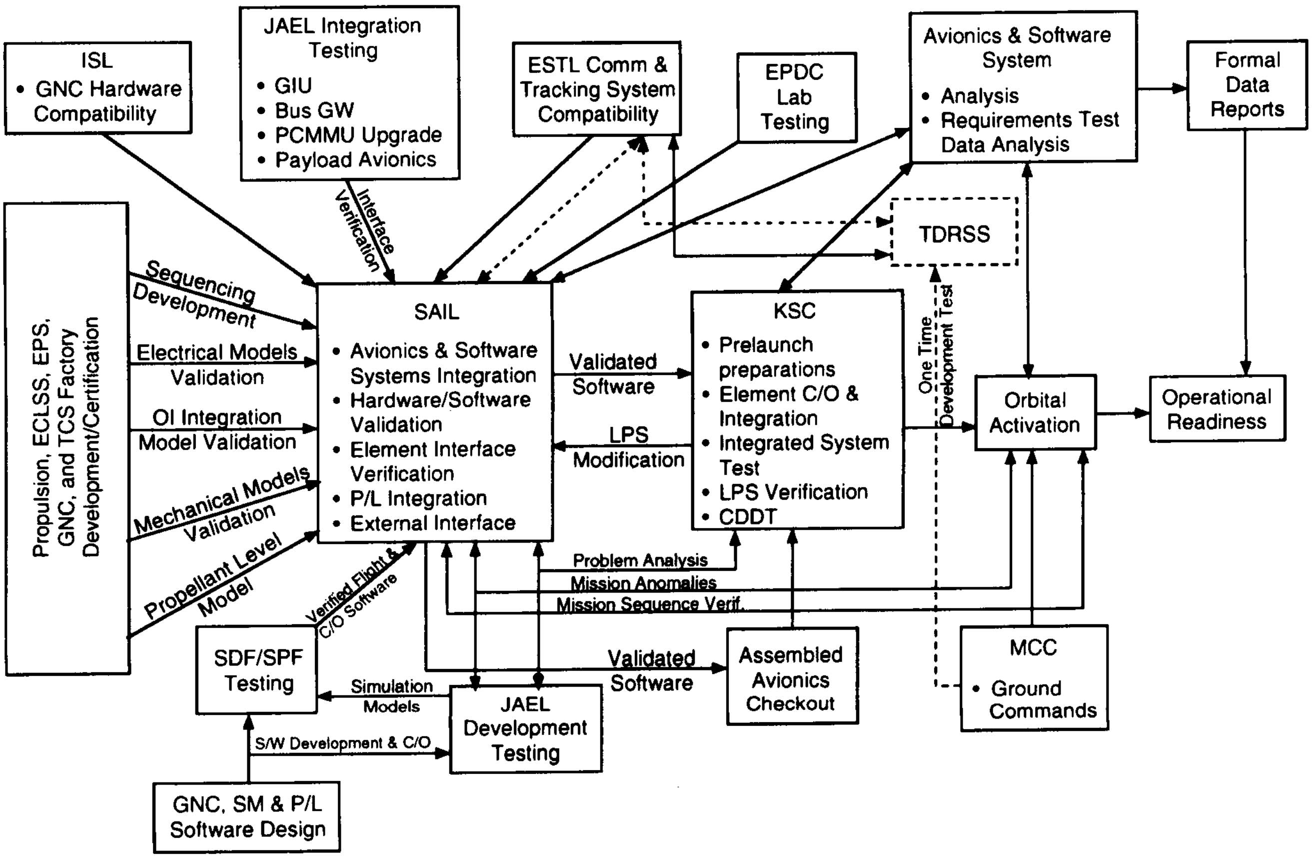
Ground Tests

These tests include integrated systems tests and final system-level tests with simulated interfaces from other systems. All systems, payloads and International Partner elements that interact with the data management system will participate in the integrated avionics testing illustrated in Figure 90 by providing a simulator of the interfaces to the laboratory. This testing will include all of the software interactions among subsystems.

The environmental control and life support system will undergo final system testing in the Engineering Test Article and Baseline Operations System Test and Manned Operational System Testing laboratories. Test complexity will build up to the final human-in-the-loop testing for water reclamation and temperature and humidity control.

Acceptance Tests

Most components and assemblies will be acceptance-tested prior to shipment to Kennedy Space Center for integration to ensure that they will perform and contain no defects. Acceptance test-



CDDT	-	Count Down Demonstration Test
C/O	-	Checkout
ECLSS	-	Environmental Control & Life Support System
EPDC	-	Electrical Power Distribution & Control
EPS	-	Electrical Power System
ESTL	-	Electronic Systems Test Laboratory
GIU	-	General Purpose Computer Initialization Unit
GNC	-	Guidance Navigation & Control
GW	-	Gateway
ISL	-	Inertial Systems Laboratory
JAEL	-	JSC Avionics Engineering Laboratory
JSC	-	Johnson Space Center
KSC	-	Kennedy Space Center
LPS	-	Launch Processing Software
MCC	-	Mission Control Center
OI	-	Operational Increment
PCMMU	-	Pulse Code Modulation Master Unit
P/L	-	Payload
SAIL	-	Shuttle Avionics Integration Laboratory
SDF	-	Software Development Facility
SM	-	Systems Management
SPF	-	Software Production Facility
TDRSS	-	Tracking & Data Relay System Satellite

Figure 90
Option C integrated avionics system verification activity

ing will be done at the highest level of assembly practicable before shipment. For example, integrated system and payload racks would be verified to the rack level prior to shipment.

Vehicle In-process and Acceptance Tests

The Kennedy Space Center verification testing is interdependent with the integration process. As system components, payloads or their utilities are installed, testing such as continuity, isolation, grounding and leak checks are performed in-process. As systems, including environmental control and life support, communication and tracking, data management, propulsion and thermal control are installed, functional tests are performed. As systems or major assemblies installations are completed (e.g., radiators, solar arrays, or docking ports), the assemblies and final interfaces are functionally tested.

When systems installation is completed and the aft fuselage is installed, module testing and integrated operations testing (including system end-to-end tests and mission sequence tests) are performed. Following the integration of the assembled on-orbit vehicle to the nose cone, interface verification tests are completed. At the Vehicle Assembly Building, the core module is mated to the external tank and solid rocket booster stack and those interfaces are verified. The launch vehicle is ready for flight readiness firing.

International Module Verification

During Space Station module integration and verification, simulators will be used to simulate the interfaces of the international modules and pressurized logistics modules. For launch of the modules, verification is performed at Kennedy Space Center.

The International Partners will perform all integration and testing of their hardware (with support from the Kennedy Space Center). Following the completion of the Japanese Experiment Module and the Columbus Attached Pressurized Module integration, a functional interface demonstration test will be performed, as required in the current Space Station Freedom baseline. The Option C interfaces will be verified by master tools and simulators.

The payload logistics module is processed prior to shipping to Kennedy Space Center for interface verification testing. User rack checkout will be performed prior to the integration of experiment racks into the pressurized logistics module. After the full complement of hardware is installed in the module, an integrated interface verification of carrier-to-core module will be performed. The pressurized logistics module interface to Option C will be verified using the "master tool" and a simulator previously verified against Option C before launch.

Orbiter Modifications

The orbiter must be modified in two areas. First, a slow-thrust thruster system must be incorporated into the orbiter attitude control system to limit the effects of plume loads on the Space Station for use during rendezvous and docking.

The second orbiter modification will add propellant transfer lines between the orbital maneuvering system tanks and the interface ring of the docking system. This change will provide an on-orbit propellant transfer capability for the orbiter to resupply propellant to Option C propellant tanks. The orbiter docking system uses a Russian docking mechanism that contains fluid couplings designed to transfer propellant from the Progress vehicle to the Mir space station. By adding lines and control valves to the orbiter, a capability similar to that of the Russian Progress vehicle is achieved.

Design Trades

A number of system and subsystem options and approaches were assessed before arriving at the Option C recommended detail configuration. Major items that were assessed but not incorporated are summarized below.

- The Space Station Freedom data management system (baseline and multiplexer or demultiplexer subsetting) was not incorporated because of remaining development and operations costs and the Option C requirement to use the Space Shuttle system during ascent.
- Ammonia as the thermal control system working fluid was eliminated due to

intolerance to freezing for off-nominal conditions.

- Rotary joints (thermal and power) were eliminated due to complexity and interference with the Japanese Experiment Module, Columbus Attached Pressurized Module and self-shadowing.
- Separate pressurized compartments and a central tunnel were eliminated to simplify system design and operational complexity, and save significant housekeeping power without sacrificing crew safety.
- The orbiter as the assured crew return vehicle was dropped in lieu of dedicated Soyuz vehicles in order to optimize the microgravity environment.
- External systems were dropped in lieu of internal systems to reduce maintenance time and increase crew time for research. The compact design reduced the external orbital replacement units to the point of not needing to perform Space Station-based extravehicular activities; therefore, the Space Station-based airlock was not included. However, it can be added later if needed for science and engineering activities.
- Three options for obtaining the aft fuselage were considered: use of the main propulsion test article hardware, a new build utilizing the structural spares available and use of Orbiter Vehicle-102. Use of Orbiter Vehicle-102 equipment was baselined for costing purposes.

Performance Capability

Option C delivers certain essential user facilities and early experiments with the launch of the core module.

Option C uses fixed solar arrays (i.e., no alpha or beta gimbal joints); 12 electrical power feeds into the pressurized volume; four independent thermal control systems; and partitioning of the core capability with respect to guidance, navigation and control, environmental control and life support system, and communications and tracking. This design, however, does have limitations. To achieve minimum continuous power (55.4 kW), it must fly in the solar inertial mode where the attached payloads look angle varies between celestial and Earth viewing once per orbit. Option C can generate substantial power in the local-vertical flight mode (28.7 kW at Beta = 0, and increased amounts at Beta > 0° by "rolling out" the Beta angle). From a control standpoint, Option C can fly with velocity vector parallel or perpendicular to the core module axis.

The majority of orbital replacement units are inside the Space Station. Extravehicular activity is orbiter-based for scheduled maintenance. The Japanese Experiment Module equipment airlock will provide capability to service science and engineering payloads that can fit through the airlock. The Option C design does not preclude adding an airlock to one of the berthing ports if required for engineering and science, but an airlock has not been included in the flight manifest or the cost estimate. The Japanese Experiment Module Ku-band antenna is currently obstructed by fixed solar arrays, but could be relocated to the top of the core module with internal wiring through the Space Station to the Japanese Experiment Module. The Japanese Experiment Module Ku-band system could be used to provide Option C with the high-definition video (up and down) and high-rate science data.

Option C design provides a single large volume of atmosphere, protected to the debris design requirement, and two dedicated assured crew return vehicles with a clear and time-efficient escape corridor. With an equivalent of a three-inch diameter hole in the pressure vessel, it takes approximately 10 minutes for the pressure to decay to eight pounds per square inch absolute. This is adequate time for the crew to board the assured crew return vehicle and secure the hatch.

Weight Summary

The Option C configuration is made up of components and systems of varied levels of maturity, ranging from operational flight-proven system from the Space Shuttle program to critical design review level of maturity from the Space Station Freedom program, and new designs. The weight margin strategy is planned accordingly, and is shown in Table 28.

Based on the above margin strategy, the overall aggregate margin requirement for Option C is 26,200 pounds. A top-level weight summary for Option C is shown in Table 29.

Option C baseline is the standard external tank at 28.8 degrees and the aluminum lithium external tank at 51.6 degrees.

Option C has more than the required margin at both the 28.8 degree inclination and the 51.6 degree inclination. Remaining weight margins at launch will be utilized for additional outfitting.

The weights and margins for subsequent shuttle flights are shown in Figures 91 and 92.

Power Summary

Option C uses fixed solar arrays (i.e., no alpha or beta gimbal joints) with 12 electrical power feeds into the pressurized volume, four independent thermal control loops to reject the heat loads; and partitioning to the core system. This design, however, does have limitations. To achieve optimum minimum continuous power, it must fly in the solar inertial mode where the attached payload look angle varies between celestial and Earth viewing once per orbit. Option C can generate substantial power in the local-vertical flight model by "rolling out" the Beta angle.

Table 28
Weight margin strategy

Category	Percent Margin
Existing shuttle components and systems	0
Minimum modification to shuttle components and systems	5
Major modifications to shuttle components and systems	10
Space Station critical design review level hardware	10
New design hardware	20
Vehicle structure	
• Primary	15
• Secondary	18

Table 29
Option C weight summary

• Launch system (less orbital vehicle)			70,200
– Shroud		4,800	
– Nose cone		3,100	
– Transition to 1307 bulkhead		7,200	
– Aft fuselage		54,700	
– External tank modifications		400	
• Orbital Vehicle (Wet)			155,300
– Primary structure		30,300	
– Secondary structure		9,900	
– Micrometeorite and orbital debris		16,900	
– Ascent avionics		600	
– Subsystems		83,000	
– Space Station Remote Manipulator System		3,500	
– Liquids and gases		11,100	
• Option C launch weight			225,500
• User racks (nominal six)			6,000
• Total launch weight			231,500
• Lift capability with standard external tank to 28.8 degrees			264,500
Weight Margin (28.8 degrees)	**33,000**		
• Lift capability with aluminum lithium external tank to 51.6 degrees			260,600
Weight Margin (51.6 degrees)	**29,100**		

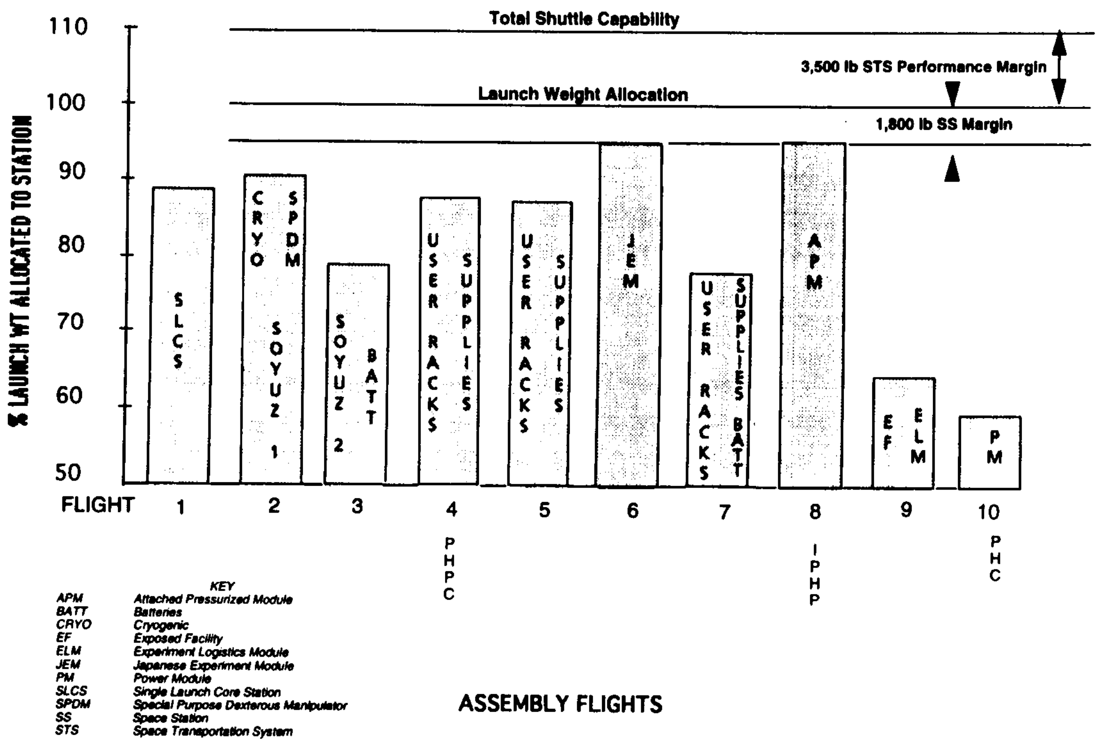


Figure 91
Launch weights for station assembly at 28.8 degrees

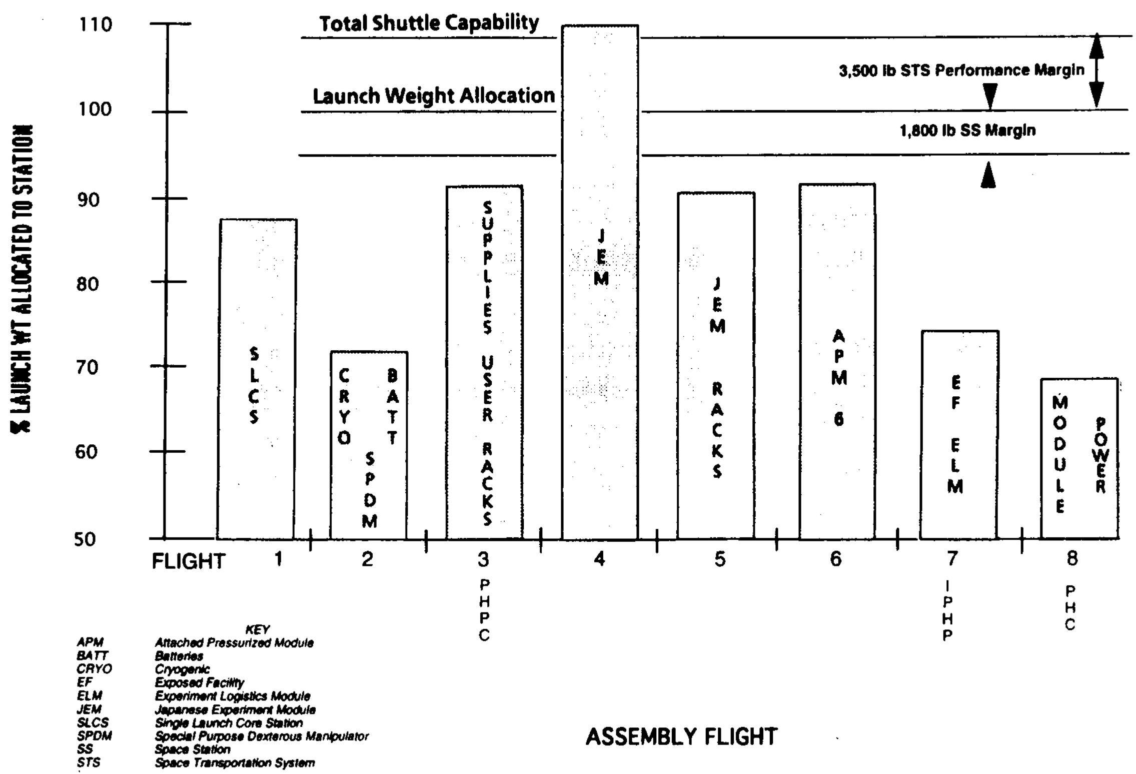


Figure 92
Launch weights for station assembly at 51.6 degrees

Specific emphasis was placed on reducing core module housekeeping power to maximize power available for users and research. A summary of core housekeeping power requirements for the Option C subsystems is shown in Table 30. When combined with International Partner elements, and housekeeping power, the total housekeeping power for Option C is 22.1 kW in local-vertical and 22.7 in solar inertial flight mode.

The power generation capability for solar inertial and local-vertical for a 12 month period is shown in Figures 93 and 94 for on-orbit inclinations of 51.6 degrees and Figures 95 and 96 for 28.8 degrees.

A third photovoltaic power module assembly will be added after the international modules are on-orbit. This power module assembly, consisting of two additional solar array wings, six array regulators, four batteries, thermal system, utilities, and a docking tunnel system.

The resulting power provided to users is contained in Table 31 for the flight modes, orbit inclinations and solar array configurations. In the six wing configuration, the solar inertial power output is limited by the vehicle heat rejection and the values have "derated" the power by 3-5 kW consistent with the affected solar inertial mode. For all other power values, the thermal system performance is matched consistent with power capability.

Safety and Reliability

Option C improves reliability by allowing full assembly and interface checkout of the Space Station module on the ground prior to on-orbit use. It reduces the multiple launch safety risk by requiring only four launches to attain Permanent Human Presence Capability. Option C significantly reduces the extravehicular activity safety risk.

Option C launches with its full complement of avionics redundancy in place. The power system contains 12 separate channels (six for initial launch) and requires only two of four photovoltaic arrays extended to keep the Space Station on-orbit. Similarly, the active thermal system has four radiator and external loops. This configuration requires only two of four radiator doors deployed to provide adequate cooling for housekeeping functions. This requirement can be reduced to only one deployed radiator by cross-strapping internal loops. The Option C design is a quasi-stable and "no freeze" configuration in Earth orbit making the Space Station tolerant to off-nominal attitude excursions and contingencies.

Option C incorporates debris shielding on all external surfaces. The shielding meets .955 probability of no micrometeoroid and orbital debris penetration in 10 years. Option C uses the three-layer shield system developed for, but not yet

Table 30
Option C core module housekeeping power summary

Comparison to Space Station Freedom Baseline	Option C	Space Station Freedom Baseline
Communications and Tracking	.90	1.06
Crew Health Care	0.10	.32
Data Management	2.30	3.48
Environmental Control and Life Support	3.00	5.41
Extravehicular Activity	0.00	.01
Flight Crew Equipment	0.20	1.43
Guidance, Navigation and Control	0.43	.53
Mechanical Systems	0.00	.20
Power Distribution and Control	0.93	1.48
Propulsion	0.22	.90
Thermal Control	2.30	1.70
Margin (10 percent on new equipment)	.67	.79
TOTAL	11.07	17.31

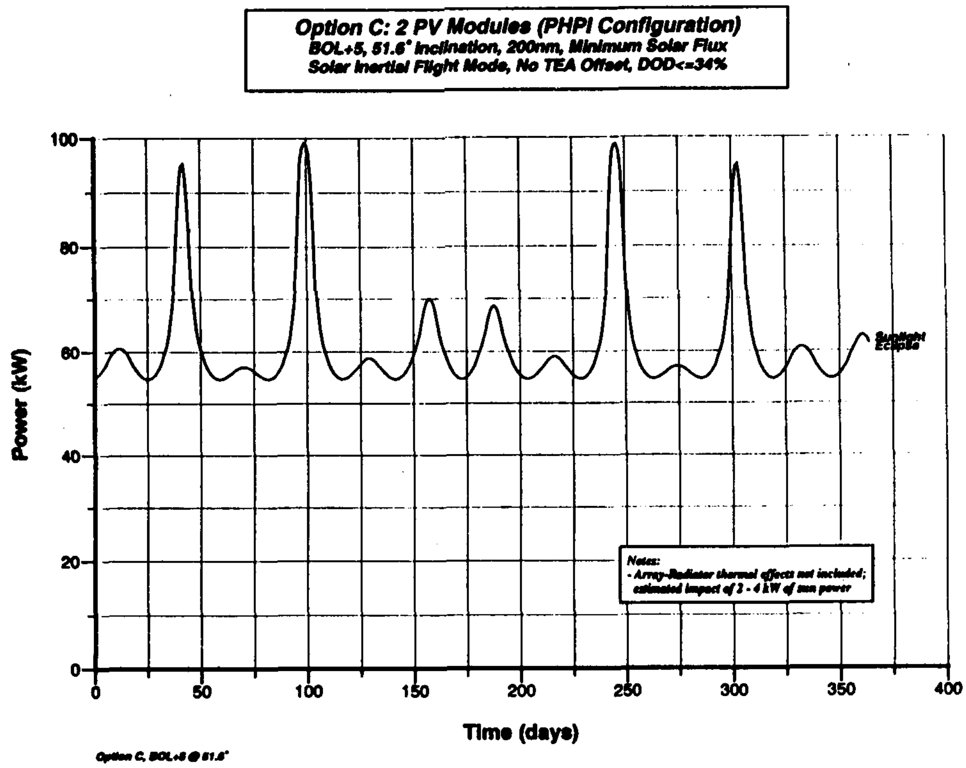


Figure 93
Option C: Two photovoltaic modules (Permanent Human Presence-International configuration)

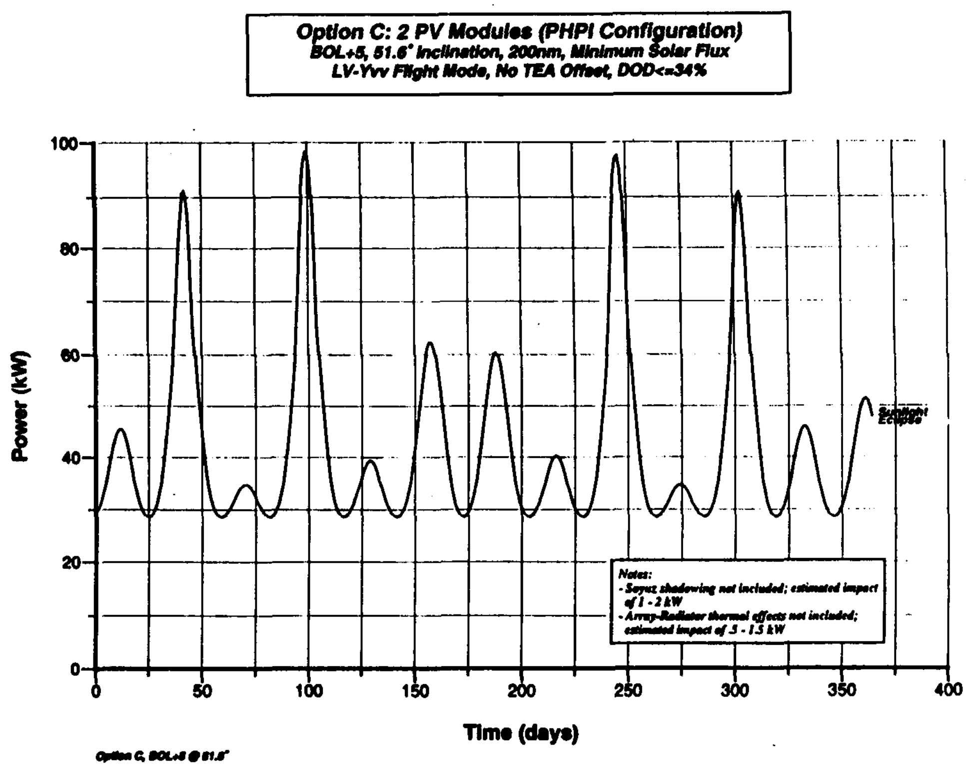


Figure 94
Option C: Two photovoltaic modules (Permanent Human Presence-International configuration)

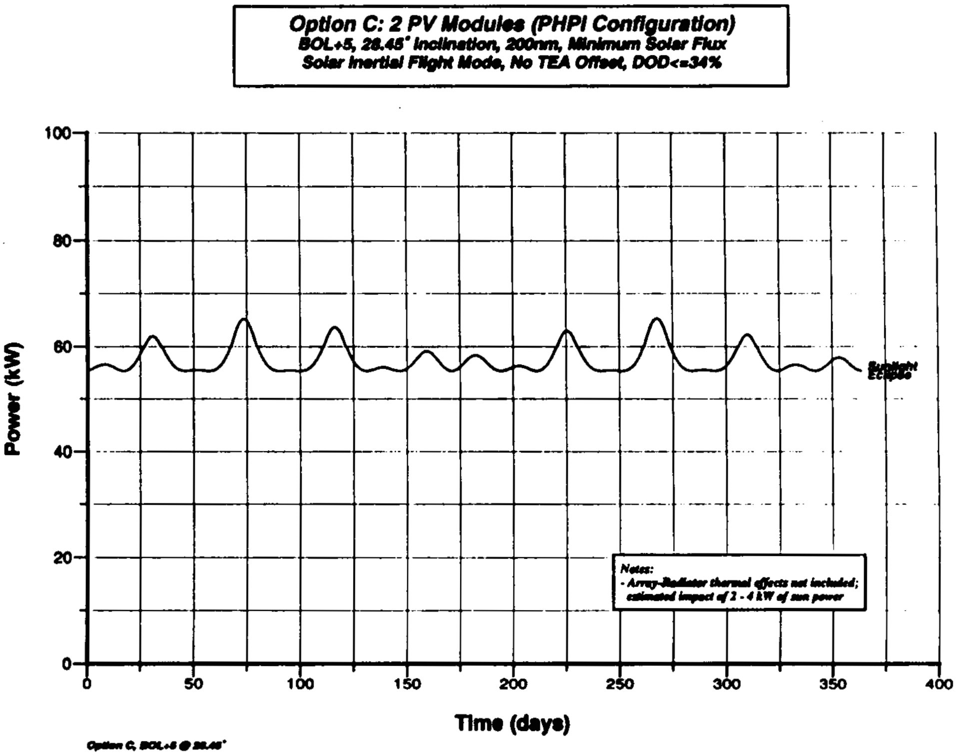


Figure 95
Option C: Two photovoltaic modules (Permanent Human Presence-International configuration)

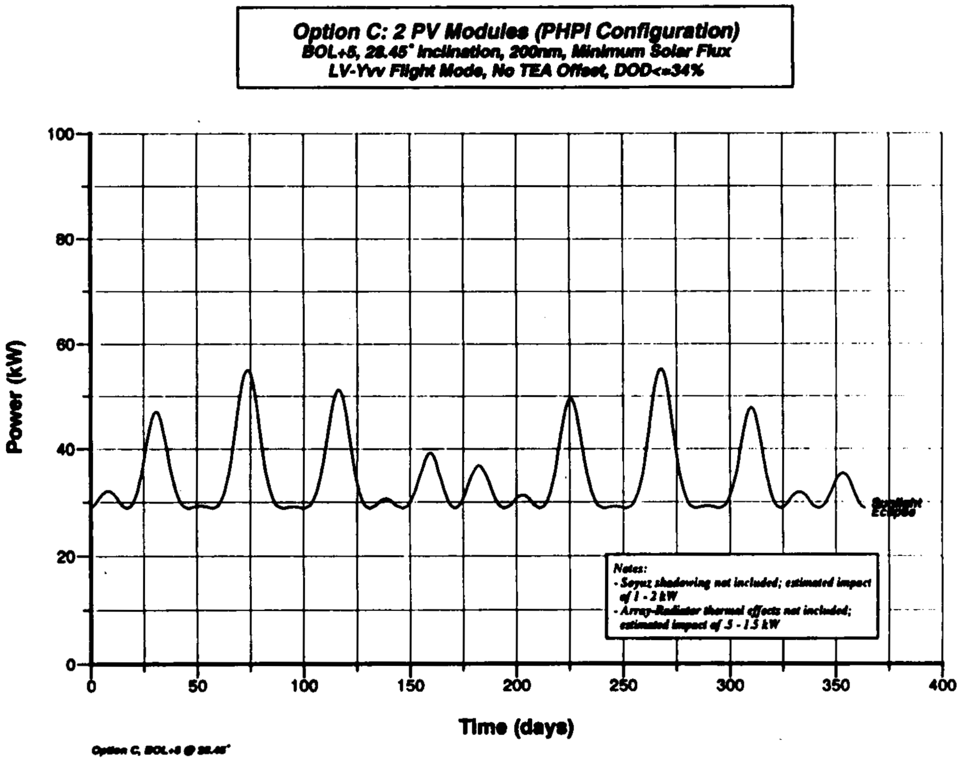


Figure 96
Option C: Two photovoltaic modules (Permanent Human Presence-International configuration)

Table 31
Available user power summary

	51.6 Degrees	28.8 Degrees
Array Configuration (solar interial and local-vertical)		
Core station without International Partners four array wings		
zero beta	43.0/17.4 kW	40.8/17.7 kW
average shade orbit	49.6/36.3 kW	45.9/23.1 kW
Core station with International Partners six array wings		
zero beta	45.6/17.5 kW	45.8/17.8 kW
average shade orbit	42.2/32.8 kW	40.2/24.4 kW

incorporated into, the Space Station Freedom baseline program. The shield is comprised of a 0.050 inches 6061-T6 aluminum outer layer, a middle layer of aluminum mesh, Nextel, Kevlar and multi-layer insulation and the 0.125 inches 2219-T87 aluminum pressure wall. Debris shield requirements drive the pressure wall thickness to .125 inches. This thickness yields a design margin of four for pressure.

The large 26,000-cubic-foot volume provides the crew approximately 10 minutes to find and repair a three-inch equivalent hole before the pressure drops from 14.7 to 8 pounds per square inch absolute. Assured crew return vehicles are provided for time-efficient access if the crew must evacuate.

Resources Available to Users

Rack Characteristics

The 26,000 cubic feet of core station volume provides accommodations for 40 user racks prior to the arrival of the international modules. The Option C design allows for the use of express racks that can be fully outfitted on the ground and carried to the Space Station for mounting into a rack location. The racks provide a standard interface allowing the use of equipment flown earlier on Space Shuttle and/or Spacelab missions.

External Payloads

Provisions are made to attach payloads on the exterior of the Space Station. Exterior attachment platforms are provided for all viewing options: Earth, solar and celestial. Three dedicated sites are available for attaching external payloads: two common berthing ports on the bottom of the Space Station and a dedicated payload attach platform on the top. In addition, there are 10 power data grapple fixture locations that could potentially be used when the Space Station remote manipulator system is not in operation. The common berthing ports can be used to attach custom-designed science modules that can be returned to Earth for re-outfitting and then reflown.

Power Availability

In the solar inertial flight mode, 30 kW is available to users with two photovoltaic arrays after Permanent Human Presence. In the local-vertical flight mode, 18 kW is available with two photovoltaic arrays. After Permanent Human Presence and with the third photovoltaic array, 40 kW is available to users in the solar inertial flight mode and approximately 18 kW is available in local-vertical mode.

Crew Availability

Reductions in external maintenance and simplification of systems account for a crew-time savings over that for Space Station Freedom. It is estimated that the crew members will be available to support user activities approximately 7,000 hours per year.

User Communications

Option C provides user downlink capabilities of 50 Mbps. Users are able to transmit one video channel at a time to the ground. Uplink telecommunications of 72 and 128 Kbps are available to users. Data interface with the user will accommodate current Spacelab protocols. High data rate (32 Mbps) data recorder and video recorders are provided along with the Spacelab interface unit to store data during communication outages.

Station Environment

The ambient atmosphere inside the Space Station will be at 14.7 psi. It contains nominal nitrogen and oxygen concentrations of 78 percent and 21 percent, respectively. Carbon dioxide concentrations are nominally controlled to less than 0.7 percent with capability to control to 0.3 percent when required. The Option C microgravity environment has more than 50 percent of the racks within the one microgravity or less envelope. Figures 97 through 100 show the microgravity level profiles for the local-vertical orientations, with both the X-axis and the Y-axis into the velocity vector. Figures 101 and 102 show the microgravity level profiles in the solar inertial mode.

Other Resources

Users are also provided an acceleration mapping system, pressurized nitrogen gas and potable water, the capability to vent waste gas, a vacuum source, payload cooling with either forced air or coldplate, two user refrigerators and freezers, a furnace for microgravity research, and a shared portable work bench for routine maintenance and repairs.

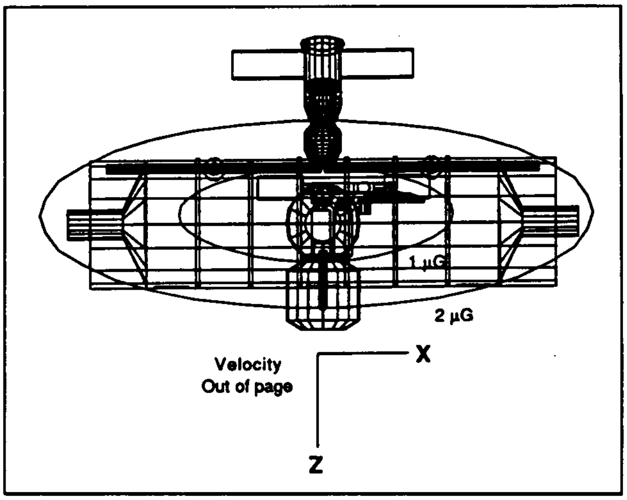


Figure 97
Option C, local-vertical (Y-axis into velocity), with International Partners, 0 degrees Beta

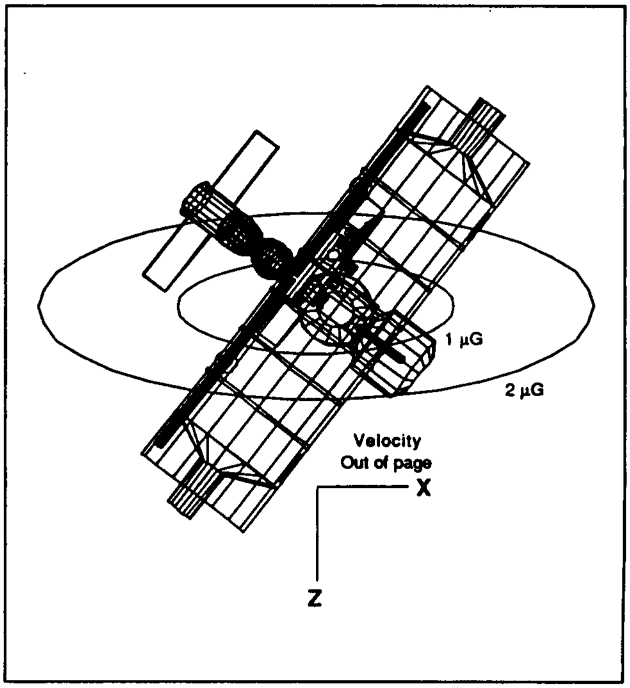


Figure 98
Option C, local-vertical (Y-axis into velocity), with International Partners, 52 degrees Beta

Optical Windows

Option C provides two 20-inch optical quality windows, one on deck six and one on deck two. On deck six, optical instruments can be rigidly mounted with a view through the window. In

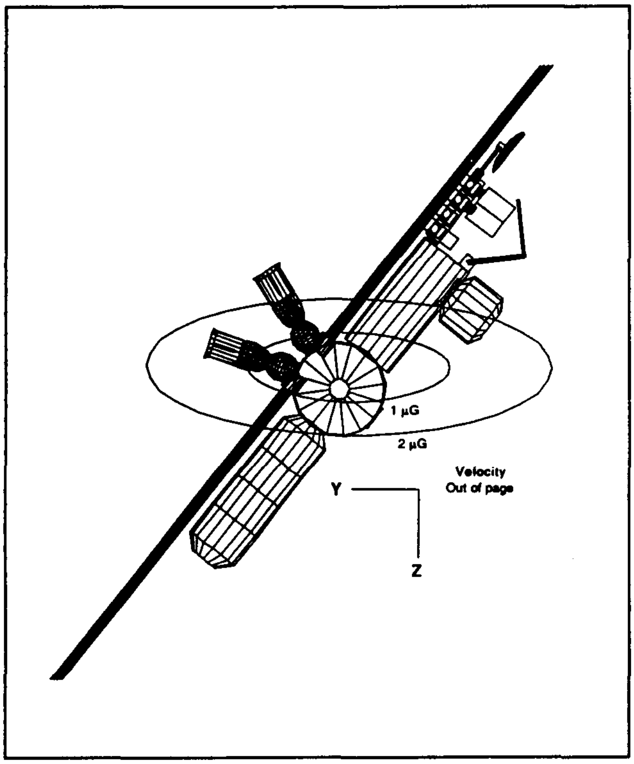


Figure 99
Option C, local-vertical (X-axis into velocity), with International Partners, 52 degrees Beta

addition, four eight-inch optical quality windows are provided.

Engineering Research

Option C provides an engineering test-bed for future technology development. Examples include the closed loop life support system, advanced space power systems such as solar cells, solar dynamic systems, power beaming from a free flyer, and advanced propulsion systems such as water electrolysis and oxygen and hydrogen propulsion.

Reduction of microgravity and improvement of the laboratory environment is feasible. A system consisting of low-thrust propulsion jets and a device for sensing acceleration was used in 1972 to counter aerodynamic drag on Stanford University's "drag-free" satellite; a similar system will be used aboard the NASA Standard Gravity Probe B spacecraft. A similar system is being considered for use on Option C. This system could potentially improve the desired microgravity environment while in the power-rich solar inertial flight mode. It could also be used as an engineering research tool to control levels of microgravity.

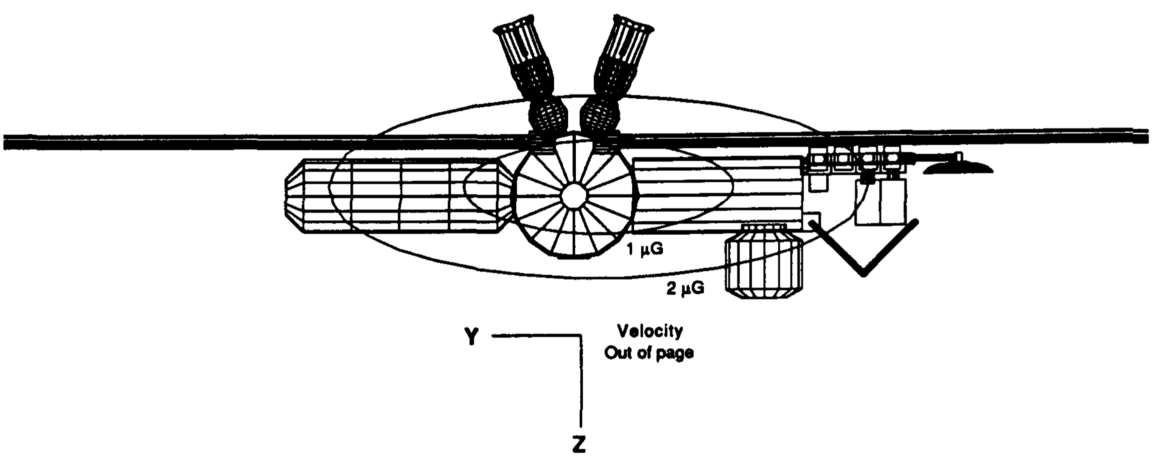


Figure 100
Option C, local-vertical (X-axis into velocity), with International Partners, 0 degrees Beta

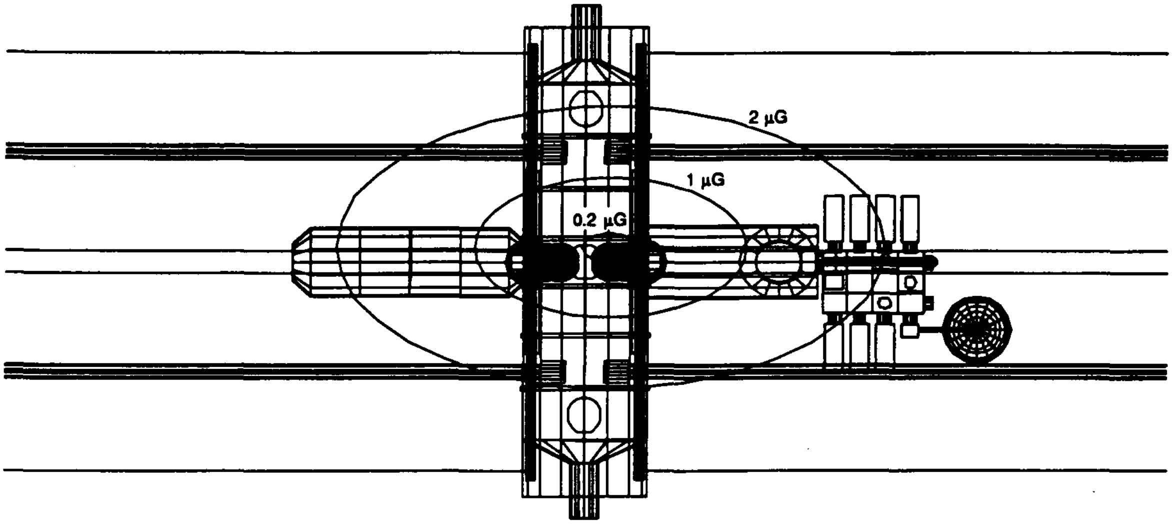


Figure 101
Option C, solar inertial, with International Partners, 0 degrees Beta

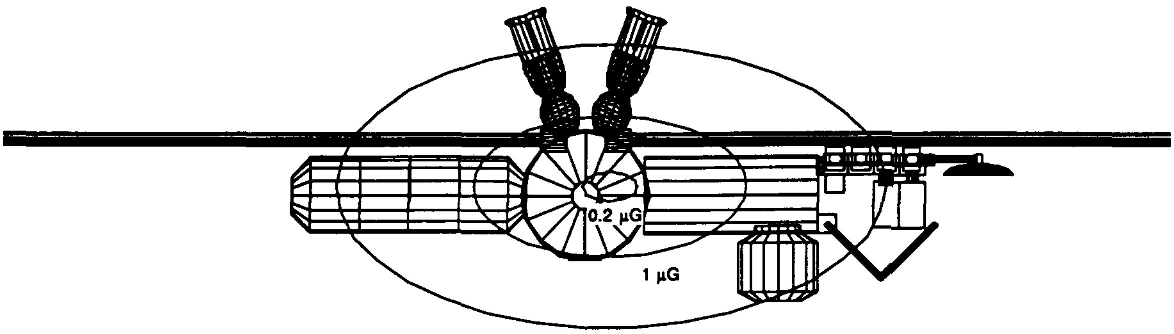


Figure 102
Option C, solar inertial, with International Partners, 0 degrees Beta

Accommodation of International Partners

The Japanese Experiment Module and Exposed Facility and the Columbus Attached Pressurized Module can be accommodated at any two of the three common berthing mechanism ports on deck four. The interfaces for data management, thermal control and communications are different from Space Station Freedom because of the different architectures within Option C. Since the alpha and beta joints have been removed from the Option C design, the overall vehicle orientation is fixed with respect to the solar array, and the view of the Earth varies with the flight mode. The Space Station Freedom photovoltaic arrays have been redesigned to provide better, but still limited, viewing capability (approximately 23-foot separation) for the Japanese Experiment Module and the Columbus Attached Pressurized Module.

Canada's Space Station Remote Manipulator System and the Special Purpose Dexterous Manipulator are included in Option C. The Space Station Remote Manipulator System will be launched on the initial flight and is stowed for launch on the external forward end of the core element with its elbow extended forward and structurally supported by the nose cone. An alternate configuration where the Space Station Remote Manipulator System is "folded" for launch, designed for Space Station Freedom, is being evaluated.

Option Specific Operations

Flight and Ground Operations

Option C eliminates much of the training, analysis, mission planning and mission execution costs that result from multiple flights and assembly tasks. Because Option C is launched as an integrated system, on-orbit assembly is not required to provide human presence capability.

The Space Station and its systems have been specifically designed to achieve a high level of synergy with the Space Shuttle to reduce operations costs. The Space Station data management system, guidance, navigation and control, and communications and tracking systems were selected so the existing Mission Control Center and Space Station Control Center are highly compatible, as well as launch processing systems. Training facilities for the crew and flight controllers are similarly highly compatible.

Vehicle Assembly, Launch Processing and Launch Site Modifications

Option C buildup, testing and integration will use existing Space Shuttle processing infrastructure at Kennedy Space Center. The schedule for delivery and processing of the elements is shown in Figure 103. Verification and test philosophy will be based on the same philosophy as that used for Space Shuttle hardware on a first-flight process.

The core module will arrive at Kennedy Space Center via the NASA barge and will be placed in the Space Station Processing Facility processing high bay. Access inside and outside will be established to support a complete receiving inspection and preintegration inspection. After the preintegration inspection is completed, secondary structures, cables and fluid lines will be installed. Components, such as fluid lines, cables and brackets will be shipped to Kennedy, ready for installation.

The nose cone will arrive at Kennedy approximately one year after the core module. The solid rocket motors will be installed in an existing hazardous processing facility in the industrial area, prior to mating the nose cone to the core module in the Space Station Processing Facility. The nose cone will be mated and an interface verification test completed.

The aft fuselage and launch element components will be available at Kennedy Space Center approximately 11 months prior to launch, and mated to the transition section to provide an integrated unit. Stand-alone processing of the aft fuselage will take approximately five months. Integration and testing of the aft fuselage with the core module will require approximately four months. Launch vehicle element integration and launch will require four months.

The orbiter Processing Facility will be used to process the aft fuselage and install the main engine. This will allow engine installation to be performed without being a serial part of the launch processing flow. The aft fuselage will be mated horizontally to the core module in the Space Station Processing Facility. Once Space

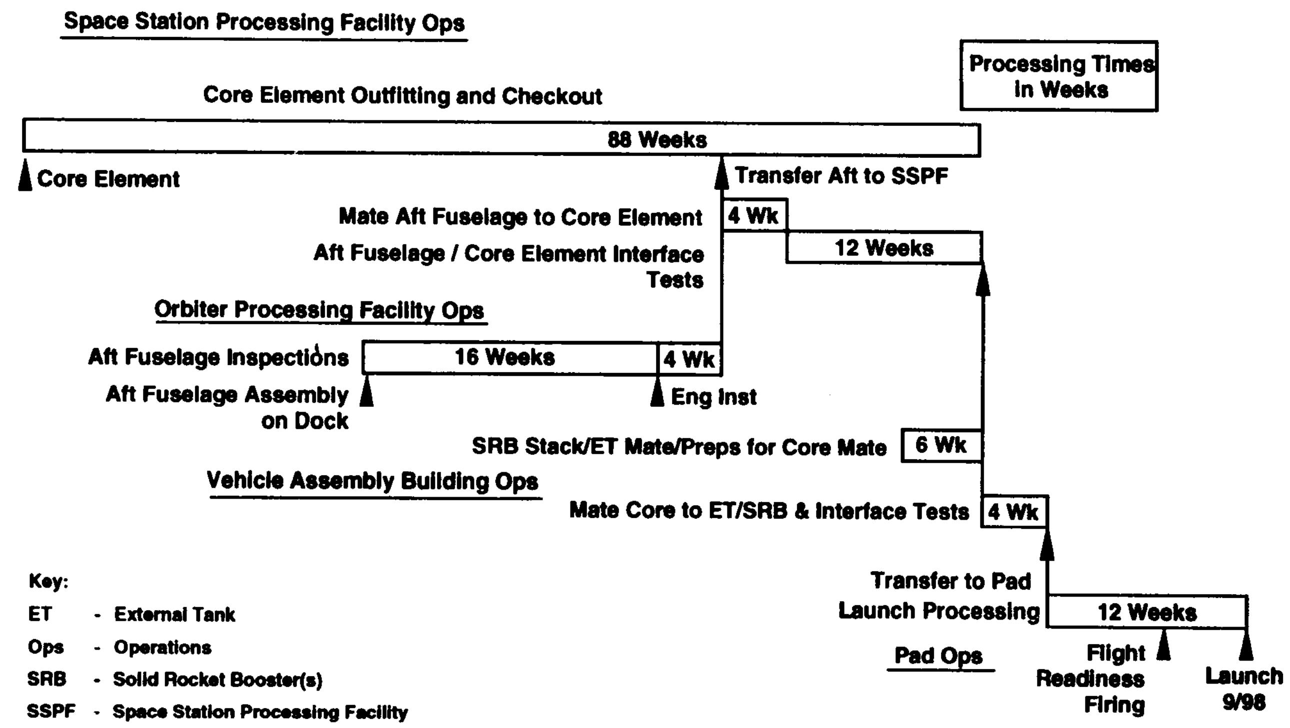


Figure 103
Kennedy Space Center processing flow

Station Processing Facility test and integration are complete, the mated aft fuselage, nose cone and core module will be transported horizontally to the Vehicle Assembly Building using the existing orbiter transport system. At the Vehicle Assembly Building, the core module will be mated to the external tank.

Module Processing

The processing and integration of the mini-pressurized logistics module, unpressurized logistics support structure, cryo carrier, Japanese Experiment Module and Columbus Attached Payload Module will be planned in series with the processing of Option C. Common handling procedures, software applications and plans will be developed consistent with today's planning for the Space Station Freedom program. The modules, equipment, and systems will be processed in the Space Station Processing Facility, and a common set of ground support equipment and test equipment will be used. This approach accommodates synergism with existing Spacelab experiment processing, and deployable payload processing and will result in lower total personnel requirements.

Pressurized Logistics Module

The processing of this module will use standard procedures, software and common schedules. Subsequent to the processing of the first flight of each mini-pressurized logistics module, an assessment of the interface will be performed to determine the need to perform an off-line interface verification on repetitive missions. The mini-pressurized logistics module will return with materials, trash, garments and samples that will be removed and processed after each flight. The mini-pressurized logistics module will undergo a complete postflight inspection and any necessary repairs before being processed for the next mission.

The unpressurized logistics support structure will be integrated and checked out prior to integrating attached orbital replaceable units and/or attached payloads. Attached payloads can be processed in a number of existing facilities, using a variety of test equipment, ground support equipment and procedures. The development of unique procedures, software applications and simulations will be limited to distinctly unique processing requirements. The unpressurized logistics support structure will be inspected and refurbished (if necessary) after the first flight and subsequent flight, and staged to support the next mission processing.

Cryogenic Carrier

The cryogenic carrier will be processed to fly on the first Space Shuttle flight to visit Option C. The processing of the carrier will include leak checks and a demonstration of the servicing ground support equipment prior to the first launch. Subsequent to the first launch of the carrier, a postflight inspection and repair (if necessary) will be performed and the carrier will be prepared for its next flight. A common set of processing ground support equipment procedures and application software will be developed to minimize recurring cost. The carrier will be serviced with cryogenic commodities (liquid nitrogen, liquid oxygen) at the launch pad as is currently planned in the Space Station Freedom program.

Japanese Experiment Module and Columbus Attached Pressurized Module

The processing of the modules will involve unique (but similar) plans, procedures, and software simulations and applications. A joint team of the International Partners and NASA will integrate and test the modules, subsystems and experiments for these missions. Following the installation of the module in a workstand in the Space Station Processing Facility, the International Partners' receiving and inspection will be performed. Subsystem checkout and test will be performed using International Partner-provided test equipment. NASA will perform an integrated test of the module, subsystems and experiments interface to the core module prior to transfer and installation in the Space Shuttle.

Pad Processing

Pad processing will include interface testing, hypergolic propellant servicing, ordnance connections, flight readiness firing and launch processing. Procedures similar to those for Space Shuttle will be used to perform the final processing for launch. Hypergolic servicing will require application software and procedural changes to account for the unique system that will be used on the Space Station. Avionics interfaces will be the same as those for the current Space Shuttle. The ground launch software sequencer will be revised to account for the unique configurations of Option C.

Test and checkout of launch systems will be performed using modified Space Shuttle ground test procedures and software. Changes to these procedures and software will be developed to account for subsystems that have unique configurations from those of the standard Space Shuttle. Electrical power distribution control, orbital propulsion system checkout, and environmental and atmospheric system control software will require extensive modifications. Other ground controlling application software will require minor changes.

Launch Site Modifications

Kennedy Space Center facilities, systems and equipment will be used to the maximum extent possible during launch site processing. However, to process the new core module and launch vehicle elements, some modifications to existing facilities will be necessary.

The Orbiter Processing Facility will be modified to check out the aft fuselage and transition structure. The Vehicle Assembly Building high bay extendable platforms will be modified to support the mating of the launch vehicle element to the Space Shuttle external tank. The Mobile Launcher Platform will be modified to access and service (interface testing, flight readiness firing, and launch countdown) the aft fuselage of the launch vehicle element. The launch pad will be modified to provide access to the transition section, service the hypergolic propulsion system on Option C and connect the solid rocket booster ordnance. The Space Station Processing Facility will be modified for the buildup, outfitting and subsystems assembly, installation and checkout of the core module and integration testing and checkout of the aft fuselage.

Maintenance and Spares

External maintenance requiring extravehicular activity is significantly reduced because the amount of hardware located external to the Space Station is reduced. This low demand permits required extravehicular activity maintenance to be performed from the Space Shuttle, thus eliminating the need for Option C-based extravehicular activities and an Option C airlock. Using a conservative estimate, approximately five extravehicular activities are anticipated per year. External maintenance can also be performed by extravehicular robotics using the Special Purpose Dexterous Manipulator.

External and internal maintenance on items of high functional criticality will be performed as soon as practical after the failure is discovered and consistent with established flight rules. Lower criticality maintenance will be performed when it can be efficiently scheduled. No large on-orbit inventory of spares is planned; only Space Station-critical spares will be on hand. Adequate failure tolerance is provided to support operations until the arrival of spares from ground storage, along with crew members trained on the specific maintenance tasks to be performed.

Logistics and Utilization Flights

For an inclination of 28.8 degrees, Option C requires five Space Shuttle flights per year for logistics: four pressurized logistic module flights and one cryogen replacement flight. Propellant carriers are not required because the propellant is transferred directly from the Space Shuttle orbital maneuvering system tanks and may be delivered as needed on any Space Shuttle flight. External spares have been reduced to a total yearly requirement of approximately 1,800 pounds. When the international modules are attached, resupply requirements increase. At 51.6 degrees some of this increase could be accommodated by Soyuz-Progress flights. The mini-pressurized logistics module can be used with no modifications, and three modules will be required.

For an inclination of 51.6 degrees, the aluminum lithium external tank has been budgeted so that only five logistics flights are required.

The cyrogenic carrier will be redesigned to accommodate four tanks to keep the resupply frequency at once per year. The required external spares will be brought to the Space Station on existing Space Shuttle flight support equipment such as the Spacelab pallet.

Schedule

Schedules consist of program milestones, core module subsystem schedules, launch vehicle schedules, Space Shuttle elements schedules, and integration assembly and checkout and launch processing schedules. The program schedule has a short design cycle because existing Space Shuttle and Space Station Freedom components are used. The dates are based on integration assembly and checkout and launch site processing requirements. The major program milestones are:

Milestone	Timeline
Program Requirement Review	Aug 93
Contract Authority to Proceed	Oct 93
Program Design Review	Mar 94
Critical Design Review	Feb 95
Core Module /Aft Fuselage Mate	Oct 98
Flight Readiness Firing	Aug 99
Space Station Launch	Sept 99

Schedule reserve has been built into the milestones leading to the Option C launch date of September 1999. After the initial launch, subsequent milestones are accomplished as follows:

Milestone	28.8 Degree	51.6 Degree
Permanent Human Presence Capability	Nov 99	Nov 99
International Permanent Human Presence	Dec 00	Oct 01
Permanent Human Capability (3rd Photovoltaic Module)	Jan 01	Nov 01

The Option C flight manifest is shown in Tables 32 and 33 for orbit inclination of 28.8 degrees and 51.6 degrees.

Table 32
Option C - launch sequence — 28.8 degree inclination

MILE STONE	FLIGHT #	LAUNCH DATE	LAUNCH TYPE	MANIFEST	LAUNCH VEHICLE	USER RACKS INCREMENTS	USER RACKS TOTAL
SLCS	1	Sep-99	ASSM	CORE STATION	SHUTTLE DERIVED	6	6
	2	Sep-99	ASSM	CRYO, SOYUZ 1, SPDM	SHUTTLE		
	3	Oct-99	ASSM	SOYUZ 2, BATTERIES	SHUTTLE		
PHPC	4	Nov-99	ASSM	USER RACKS, SUPPLIES	SHUTTLE	7	13
	5	Feb-00	ASSM	SUPPLIES & USER RACKS	SHUTTLE	9	22
	6	Apr-00	ASSM	JEM MODULE	SHUTTLE		
	7	May-00	USER/LOG	SUPPLIES, USER RACKS, BATTERIES	SHUTTLE		
	8	Aug-00	USER/LOG	SUPPLIES & USER RACKS	SHUTTLE		
	9	Oct-00	ASSM	APM MODULE	SHUTTLE		
	10	Nov-00	LOG	SUPPLIES, CRYO & USER RACKS	SHUTTLE		
IPHP	11	Dec-00	ASSM	EF & ELM	SHUTTLE		
PHC	12	Jan-01	ASSM	PV MODULE	SHUTTLE		

SLCS = SINGLE LAUNCH CORE STATION
PHPC = PERMANENT HUMAN PRESENCE CAPABILITY
IPHP = INTERNATIONAL PARTNERS HUMAN PRESENCE
ASSM = ASSEMBLY FLIGHT
LOG = LOGISTICS FLIGHT
SPDM = SPECIAL PURPOSE DEXTEROUS MANIPULATOR
MPLM = MINI-PRESSURIZED LOGISTICS MODULE
JEM = JAPANESE EXPERIMENT MODULE
APM = ATTACHED PRESSURIZED MODULE
EF = EXPOSED FACILITY
ELM = EUROPEAN LOGISTICS MODULE
PV = PHOTOVOLTAIC
INCR = INCREMENT
PHC = PERMANENT HUMAN CAPABILITY

Table 33
Option C - launch sequence — 51.6 degree inclination (aluminum lithium external tank)

MILE STONE	FLIGHT #	LAUNCH DATE	LAUNCH TYPE	MANIFEST	LAUNCH VEHICLE	USER RACKS INCREMENTS	USER RACKS TOTAL
SLCS	1	Sep-99	ASSM	CORE STATION	SHUTTLE DERIVED	6	6
	2	Sep-99	ASSM	CRYO, SPDM, BATTERIES	SHUTTLE		
	3	Sep-99	ASSM	SOYUZ 1	RUSSIAN		
	4	Nov-99	ASSM	SUPPLIES, USER RACKS	SHUTTLE	5	11
PHPC	5	Nov-99	ASSM	SOYUZ 2	RUSSIAN		
	6	Dec-99	ASSM	JEM MODULE W/ SYSTEM RACKS	SHUTTLE		
	7	Feb-00	ASSM	SUPPLIES, JEM SYSTEM RACKS	SHUTTLE	10	21
	8	Apr-00	USER	USER RACKS	SHUTTLE		
	9	May-00	USER/LOG	SUPPLIES & USER RACKS	SHUTTLE		
	10	Aug-00	USER/LOG	SUPPLIES & USER RACKS	SHUTTLE		
	11	Oct-00	LOG	CRYO, SUPPLIES	SHUTTLE		
	12	Nov-00	LOG	SUPPLIES & USER RACKS	SHUTTLE		
	13	Dec-00	ASSM	ESA, APM-6 W/ SYSTEM RACKS	SHUTTLE		
	14	Feb-01	ASSM	SUPPLIES & USER RACKS, APM SYSTEM RACKS	SHUTTLE		
	15	May-01	LOG	SUPPLIES & USER RACKS	SHUTTLE		
	16	Aug-01	LOG	SUPPLIES & USER RACKS	SHUTTLE		
IPHP	17	Oct-01	ASSM	EF & ELM	SHUTTLE		
PHC	18	Nov-01	ASSM	PV MODULE	SHUTTLE		

SLCS = SINGLE LAUNCH CORE STATION
PHPC = PERMANENT HUMAN PRESENCE CAPABILITY
IPHP = INTERNATIONAL PARTNERS HUMAN PRESENCE
ASSM = ASSEMBLY FLIGHT
LOG = LOGISTICS FLIGHT
SPDM = SPECIAL PURPOSE DEXTEROUS MANIPULATOR
MPLM = MINI-PRESSURIZED LOGISTICS MODULE
JEM = JAPANESE EXPERIMENT MODULE
APM = ATTACHED PRESSURIZED MODULE
EF = EXPOSED FACILITY
ELM = EUROPEAN LOGISTICS MODULE
PV = PHOTOVOLTAIC
INCR = INCREMENT
PHC = PERMANENT HUMAN CAPABILITY

Space Station Freedom Requirements Not Incorporated

The Option C Space Station is tailored along the requirements for the Space Station Freedom program and in all cases meets the derived safety and user requirements. There are numerous cases in Space Station Freedom program documentation where the requirements are design-dependent and not applicable to the Option C design. Major differences include:

- Interfaces with International Partners are met functionally; the detail technical interfaces will require re-negotiation.
- Solar arrays will be nonarticulating rather than utilize rotary joints to track the Sun.
- 30 kW of continuous power is provided to users only in solar inertial flight mode.
- Flight operational software will use the HAL/S high-order language maintained for Space Shuttle program instead of Ada.
- Data management system protocols will utilize Space Shuttle and Spacelab telemetry formatting conventions (time division multiplexing) rather than international standard protocols.
- Use of a Space Shuttle-derived vehicle for the initial launch.
- Support only one channel of downlink video at a time.
- Nadir viewing supported in local-vertical flight mode.
- No airlock for Space Station; all extravehicular activity is orbiter-based.
- The mobile transporter is not required.

Russian Participation

Introduction

After consulting with the International Partners concerning the scope of discussions, NASA invited the Russian space agency as well as several Russian aerospace contractors to come to Crystal City for consultations on a variety of subjects. The Russians sent 15 engineering experts to brief the Station Redesign Team on their experiences with long-duration space flight and to assist the team in assessing the capabilities and use of Russian systems. Discussions were held on the capabilities of their launch vehicles, Soyuz spacecraft, rendezvous and docking systems, and environmental control and life support systems, as well as Mir operations and science.

This section discusses Russian systems that have been baselined for use in the station redesign options, the Soyuz assured crew return vehicle and the androgynous peripheral docking assembly. It also covers Russian environmental and life support systems, the automated rendezvous and docking system and use of Mir for early science activities.

Russian launch vehicles are described in the Common Option Considerations section of this report, and in Appendix E.

Soyuz

The Soyuz spacecraft has been in service since 1967. This space system has flown over 70 missions and is in its third evolutionary configuration. NASA completed a preliminary technical feasibility study in 1992 which determined that the Soyuz can be modified for use with the Space Station as an interim assured crew return vehicle.

Soyuz crew members are currently required to wear pressure suits to protect against possible cabin pressure loss, as occurred during an early mission of the original Soyuz. This requirement is undesirable for an ill or injured crew member or for a rapid crew escape mission.

Soyuz Design Parameters	
Modules	Orbital Module, Descent Module, Instrument Module
Weight	15,583 pounds
Length	23 feet
Diameter	maximum diameter of 8.9 feet
Deployed solar array wingspan	34.8 feet
Crew accommodations	1 to 3 persons
Flight duration	3.2 days autonomous; 180 days docked to Mir

The Soyuz can nominally accommodate a crew of three, or a crew of two when considering return of an ill or injured crew person with room for medical equipment. For a four-person Space Station this drives the need for two vehicles at the Space Station with a combined continuous stay-alive power requirement of 460 to 880 Watts.

The Soyuz can target to a point 35 nautical miles to either side of its ground track and land within an area, based on dispersions, of plus or minus 16 nautical miles. The Soyuz is not recommended for a water landing. A Space Station inclination of 28.8 degrees forces landing outside of the United States. Australia would be the prime landing site. The communications system employed for Soyuz would have to be modified to be compatible with the NASA Tracking and Data Relay Satellite System or ground stations. The Soyuz is not designed for full autonomy; the state vector and deorbit targeting are developed on the ground and typically uplinked through

Mir to the Soyuz and are required to be less than 24 hours old for reasonable accuracy. Typically the Soyuz retains enough consumables for two days of orbit operations before reentry.

Studies indicate that the service life can be extended from the current six months to approximately two to three years by modifications to the battery, environmental control and propulsion systems.

NASA and the Soyuz contractor, have agreed to adopt a "no space suit" entry mode as normal assured crew return vehicle operations. Cabin pressure equalization and oxygen venting will require some hardware changes. In a more general operations approach, the Soyuz assured crew return vehicle operations would be under the control of the NASA Mission Control Center with detailed technical support provided through a communication link with the Russian Flight Control Center.

The Soyuz will require power, thermal, data and other interfaces with the station. All conversion equipment required for compatibility of the Soyuz with Space Station subsystems would be housed in an adapter, minimizing modifications required to both the Soyuz and the Space Station. These modifications are currently being evaluated by NASA and Russian engineers.

Ongoing studies deal with integration of Soyuz in the Space Shuttle payload bay, as well as modification of Kennedy Space Center facilities to accommodate the Soyuz as a Space Shuttle payload. Although the analysis is incomplete, for purposes of this study, it is assumed that two Soyuz vehicles will fit in the payload bay.

Finally, for delivery to the 51.6 degree inclination orbit, the best delivery solution would probably be via a Soyuz launch vehicle either with or without a crew. Since no Russian launch vehicle can deliver the Soyuz to 28.8 degree inclination orbits, the Space Shuttle would be the delivery vehicle.

Rendezvous, Proximity Operations and Capture System

The following Russian capabilities which utilize an automated rendezvous, proximity operations and capture system have potential application in the Space Station redesign options:

- Use of the Soyuz for the transport of crew to and from the Space Station to complement the Space Shuttle or to serve in a contingency situation if the Space Shuttle were not available.
- Use of the Progress M resupply space vehicle for material, equipment and consumable delivery.
- Use of the androgynous peripheral docking assembly for the Space Shuttle, Soyuz and Progress M vehicle capture.
- Delivery of large modules to the Space Station using expendable launch vehicles and automated rendezvous and docking or grapple for berthing.

The Soyuz and Progress spacecraft and Russian Space Station modules nominally perform automated rendezvous and docking with Mir. The system is reliable and operationally proven in use eight years with over 60 dockings. The ground operators and onboard crew closely monitor this automated rendezvous and docking system and provide corrective actions for selected contingencies to insure reliability, safety and mission success.

The Russian automated rendezvous and docking system consists of guidance, navigation and control software, computer and navigation sensor hardware, docking mechanism, systems redundancy management, and fault detection, isolation and reconfiguration. The automated rendezvous and docking system is essentially the same in the Soyuz crew transport and Progress M resupply spacecraft and on modules for delivery to Mir.

NPO Energia recently conducted its first space flight test of the androgynous peripheral docking assembly with the successful docking of a Soyuz spacecraft to Mir. The androgynous peripheral docking assembly was developed for docking the Russian space shuttle Buran with Mir but to date this has not been accomplished. Both the Soyuz and Progress vehicles nominally use a probe and drogue docking mechanism. Replacement of the probe and drogue with the androgynous peripheral docking assembly will potentially permit the use of a common system for both the Russian Soyuz and Progress and the United States' Space Shuttle. NASA is currently evaluating this system for use on the Space Station. Recent analysis suggests a significant modification may be required to ensure loads compatibility with the Space Station Freedom based designs. For purposes of this study, the modified androgynous peripheral docking assembly is baselined for all three design options.

Environmental Control and Life Support System

The Russian space program has accumulated almost 20 years of Space Station life support experience. An evolutionary design approach has been utilized to modify systems based on operational experience. The Mir potable water recovery system is a much improved version of a similarly designed recovery system first used on Salyut 4 in 1974. In other cases, life support design solutions were driven by available resources and capabilities. Systems are designed to minimize power requirements since power is limited on Mir, and to minimize logistics since the upmass and downmass capabilities of the Progress and Soyuz resupply vehicles are limited.

To minimize logistics, Mir utilizes a number of regenerative life support systems. Most of these systems are sized to support a normal crew of two or three. Thermal cooling is provided for most life support components by a water glycol system. Exceptions include high power equipment such as the condensation collection system which uses freon as a coolant. Most elements operate in an autonomous mode with only a minimal number of sensors used to monitor system health. Life support functions are compartmentalized on Mir with dependent systems located in the same module. Potable water is only available at a single location and air ventilation is provided by ducts which run inside the cabin and through hatch openings.

Water and air quality on Mir are not routinely measured on-orbit. Real-time monitoring is used to determine the concentrations of oxygen, carbon dioxide, hydrogen and water in the cabin atmosphere, but the presence of other potential trace contaminants cannot be detected. Air filter samples and air samples from returning Soyuz spacecraft are analyzed to determine the overall cabin atmosphere quality. Drager tubes can be used in emergencies to determine if one of four preselected contaminants is present in the cabin (e.g., one tube can detect propellant leaks in the cabin). Water samples are also returned to Earth for analyses approximately every six months by returning Mir crews. In situations where there is suspicion regarding potable water quality, on-orbit total microbial content analysis can be performed.

Overall, the information collected to date on the life support equipment has been insufficient to perform a complete assessment, therefore follow-up reviews are required. To perform a valid comparison of United States and Russian life support systems, detailed documentation outlining design requirements, operational performance requirements and measured value, test conditions, test results and analytical methodologies will be needed. Selected systems should undergo a 6 to 12 month test program at the same facilities where the current Space Station life support hardware is being developed to enable an adequate comparison. At the end of this ground test program a decision could be made to flight test the most beneficial systems and utilize these systems as a testbed on the Space Station.

Mir Utilization

The Space Shuttle is scheduled to fly to Mir in 1995. A United States astronaut will have been onboard Mir for three months participating in several United States and American life science experiments. This astronaut will then return to Earth, with one or two cosmonauts, in the Space Shuttle. Additional Mir capabilities for the conduct of a scientific program expanded from the baseline Space Shuttle and Mir program are being explored. This enhanced program could include the following:

- Flight of one United States crew member on Mir, twice per year through 1997 (approximately the end of life for Mir)
- Placement of United States payloads on Mir in the Spektr and/or Priroda modules, with an emphasis on life sciences. Placement of the payload onto Mir could occur as early as 1995 and the data would be collected through 1997.
- Use of the Space Shuttle to extend the life of Mir and enhance its capability to perform useful science and technology research.

The following options for United States payload accommodation on board these Mir modules were considered:

- Use of available payload space on Spektr. Approximately 1 kW, 100 kg, and 2-3 cubic meters of volume could be available for United States payloads; launch and operations could occur in January 1995, preceding the Space Shuttle/Mir mission, depending on payload availability. Payloads requiring crew members as test subjects or other crew interaction for operation would be moved from Spektr to the Mir core module for operation.
- Use of available space on Spektr and retrofit of Priroda as a research laboratory. Less than 2 kW, 1500-2000 kg, and 5-6 cubic meters of volume could be available for United States payloads.

Launch of Spektr and operations would occur in January 1995, and launch of Priroda would occur in the third quarter of 1995, depending on payload availability.

The Russian Space Agency has been given a detailed list of United States payloads for accommodation in Spektr and Priroda and will report back on the results of their analysis in the next few weeks.

Scientific objectives under consideration for the enhanced Space Shuttle/Mir program include:

1. Understanding of health risks from long-duration missions
2. Determination of trends in adaptations to long-term space flight and implications to postflight performance
3. Validation of existing countermeasure effectiveness
4. Understanding plant physiology and seed-to-seed development in space
5. General gravitational biology
6. Effects of long-term space flight on piloting skills
7. Biotechnology
8. Acceleration and vibroacoustic mapping

NASA and the Russian Space Agency are both exploring the possible implementation of a program to use the Space Shuttle to support enhanced Mir operations and improve science and engineering research.

Operations

Introduction

The Station Redesign Team developed an operations concept that supports the redesign effort and reduces the operating costs by a factor of two from the current Space Station Freedom Program estimates. This approach, which achieved significant changes in the operations concept and even more significant reductions in operations costs, was developed by a multicenter cooperative team.

The operations budget pays all program costs from the time that flight hardware is delivered to the Kennedy Space Center for prelaunch processing. This budget also pays for all program spares. The operations and utilization capability budget pays for the development costs associated with implementing much of the operations activity.

Space Station Operations Concept

The first priority is to maintain the health and safety of the Space Station crew and the integrity of the Space Station. The second priority is to ensure the user community and the International Partners are provided with a capable orbiting research laboratory while balancing cost, user support capability and schedule within the constraints established.

Overview

Success of the Space Station as an orbiting research laboratory will be determined over its 10 year operational life, not on one specific mission, flight or experiment. The Space Station will have a 24-hour autonomous survival capability without crew or ground intervention. This is critical to reducing operations costs because training and ground monitoring and control can be kept to a minimum.

The Space Station must be designed to allow for incremental failures that permit operations to continue. This graceful degradation of systems is a fundamental requirement throughout the design process. Therefore, in addition to redundancy in critical systems, adequate spares must be available on board. Probability versus possibility risk analysis will be utilized in on board system design and in formulating Space Station command and control guidelines and training priorities.

The Space Station crew will be on-orbit for extended periods of time. This provides an opportunity to obtain scientific data without the present timeline constraints of Space Shuttle and Spacelab missions. If noncritical systems or scientific experiments fail and cannot be repaired on-orbit, then replacement units or spares are sent on the next flight. An assured crew return capability will be available at all times a crew is on board the Space Station.

Command and Control

A structured flight crew organization is used to coordinate and accomplish planning, mission objectives and other duties. The crew commander will have final authority and responsibility for all activities conducted on board the Space Station. Mission planning will be conducted on the ground with the mission objectives modified as necessary based on scheduled and periodic updates and on inputs from the user community. The crew has the flexibility and the autonomy necessary to conduct their own activities and scheduling. A cyclic pattern of established operations will also be utilized for most activities. This cycle will include periods for maintenance, housekeeping, rest and recreation.

The operations director, as head of the Mission Control Team, is responsible for the real-time implementation of overall operations within the framework of the mission rules. The operations director has final authority and responsibility for all ground actions to ensure crew safety and vehicle integrity. A Space Station Mission Management Team, which includes representatives of the users and International Partners, provides programmatic guidance to the operations director.

There will be both a crew and an automated onboard capability to monitor and control all safety critical functions during normal and contingency operations without ground support. The Space Station design allows the manual override of critical systems by the crew. Similarly, these systems are monitored and can be controlled at the Space Station Control Center.

The Space Shuttle Flight Control Team will control all Space Station activities during the assembly phase, when the Space Shuttle is on-orbit. The Space Station Control Center will assume control for all proximity operations after permanent human presence capability is achieved. The Space Station Control Team will control the Space Station at other times.

During untended operations, the Space Station design provides for ground monitoring and limited control by a small mission control team. This ground team will manage telemetry and command systems, adjust Space Station attitudes and the orbit and ensure the proper operation of environmental and pressurization systems. During human tended operations, the ground team will be augmented on the prime shift to perform systems and resources trend analysis and to provide the planning interface between onboard scientists and their ground research counterparts, located remote to the control center.

Payload Control

On-orbit research control will be under the jurisdiction of the Space Station commander. The crew commander will designate a payload crew member to serve as lead manager of payload planning, scheduling and operations. This crew member will coordinate payload activities with the Payload Operations and Integration Center.

Streamlined and responsive payload operations support to users will be provided through one research and science control facility. Researchers and principal investigators around the world will operate as an extension of the science control team and will be provided with command and data services. Direct voice communication with the astronauts performing their research tasks will be enabled as required.

Sustaining Engineering

The sustaining engineering force of past programs, which was comprised of a significant carryover of development contractors, will be replaced by a small cadre of NASA and specialized contractor personnel. Their goal will be to ensure that the Space Station and its systems provide a safe and reliable on-orbit laboratory facility with the capability to support the evolving research objectives while controlling the cost. This cadre also forms the core of the team that can be called upon to address the resolution of Space Station anomalies.

Maintenance

Maintenance will be limited to orbital replacement units for most systems. The onboard crew will be trained in the operation, troubleshooting and repair of systems required for crew or Space Station survivability. A mission essential list shall be developed, identifying those subsystems that are critical to allowing the mission to continue. This mission essential list will determine the requirements for spares, redundancy and training. Critical systems will have built-in redundancy but spares may be required for certain designated items. However, no system will be designed to preclude repair or maintenance access. Reliability and quality assurance functions will become integral parts of the maintenance function.

External replacement or repair of systems or experiments will be accomplished using remote manipulators when possible. Extravehicular activity will be accomplished by astronauts brought up by the Space Shuttle. For Options A and B, Space Station astronauts will receive basic extravehicular activity training for contingency. Due to the relatively low amount of external equipment, Option C is baselined without an airlock, so all extravehicular activities must be performed from the Space Shuttle.

Operations Support Functions

The goal of these support functions is to provide the most productive and cost-effective payload utilization while ensuring vehicle and crew safety. The subsequent sections discuss the content of these functions and describe the steps necessary to achieve the cost reductions presented in the Cost Section of this report.

Utilization Operations

Utilization operations encompasses the payload functions from the initial definition of the payload for flight through the onboard operation and return of the data to the user. Utilization and operations requirements, plans and activities must be integrated across the NASA centers and the International Partners. The streamlining and downsizing of the management and integration of this overall process at the program level are discussed in the Management Section of this report.

Payload operations begins with assisting the user in the process of planning. Payloads operations also includes the development of operations documentation, training of the flight and ground teams, including the users, and executing the planned mission to meet the needs of the user. The science and technology communities which form the Space Station users will operate and be accommodated in a process similar to the recent Spacelab missions where payload activities were integrated by the users. The users will operate in a streamlined mode from their home facilities. Payload commands will be routed through the Payload Operations Integration Center, the single research and science control facility which will coordinate the experiments on the Space Station. This center provides 24-hour a day payload command and control capability for the user as well as voice interface with the crew. The payload control center team integrates the needs of the worldwide user community and works with the users and the Space Station Control Center team to achieve mission objectives and resolve payload conflicts. Researchers and principal investigators around the world will operate as an extension of the science control team and will communicate directly with the astronauts doing their research. An example of a research control architecture is shown in Figure 104.

The utilization operations cost reduction effort had two major thrusts. First, the payload integration process was streamlined and shortened significantly. Second, the planning effort was reduced from the Space Station Freedom approach to reflect a planning approach where success is measured over 10 years. In streamlining the payload analytical integration and physical integration processes, full advantage was taken of the standardized payload accommodations, the International Standard Payload Rack, and the concept of "express" racks where the user can be assigned as late as 11 months before launch for simple payloads. An express rack accommodates payloads which are preintegrated into subrack enclosures, such as drawers or lockers, that plug into standard interfaces in the rack. Significant cost savings were found by reducing the payload analytical integration schedule span from three to five years to 24 months. Express rack payloads allow further decreases in premission support. The premission planing template was reduced from 24 to 12 months.

During the mission, relaxed planning for scheduled activities avoids the need for extensive and costly real-time support. If an activity is not accomplished, it can be rescheduled for another time depending on the situation. For the human-tended assembly and utilization flights, optimized replanning will be accomplished, but will occur on a 24-hour cycle. For the untended and permanent human capability phases, replanning is accomplished on a weekly cycle, or sooner, depending on the magnitude of the change. This planning philosophy will lower operations staffing costs by reducing the number of iterations required to develop a typical planning product and the number of increments in the planning template at any one time.

The Payload Operations Integration Center will provide full time team support during human tended and utilization flights and will provide a lower level of support during the untended and permanent human presence capability phases. In all cases, the team staffing has been reduced from that of previous Space Station Freedom plans. Staffing reductions are shown in Table 34.

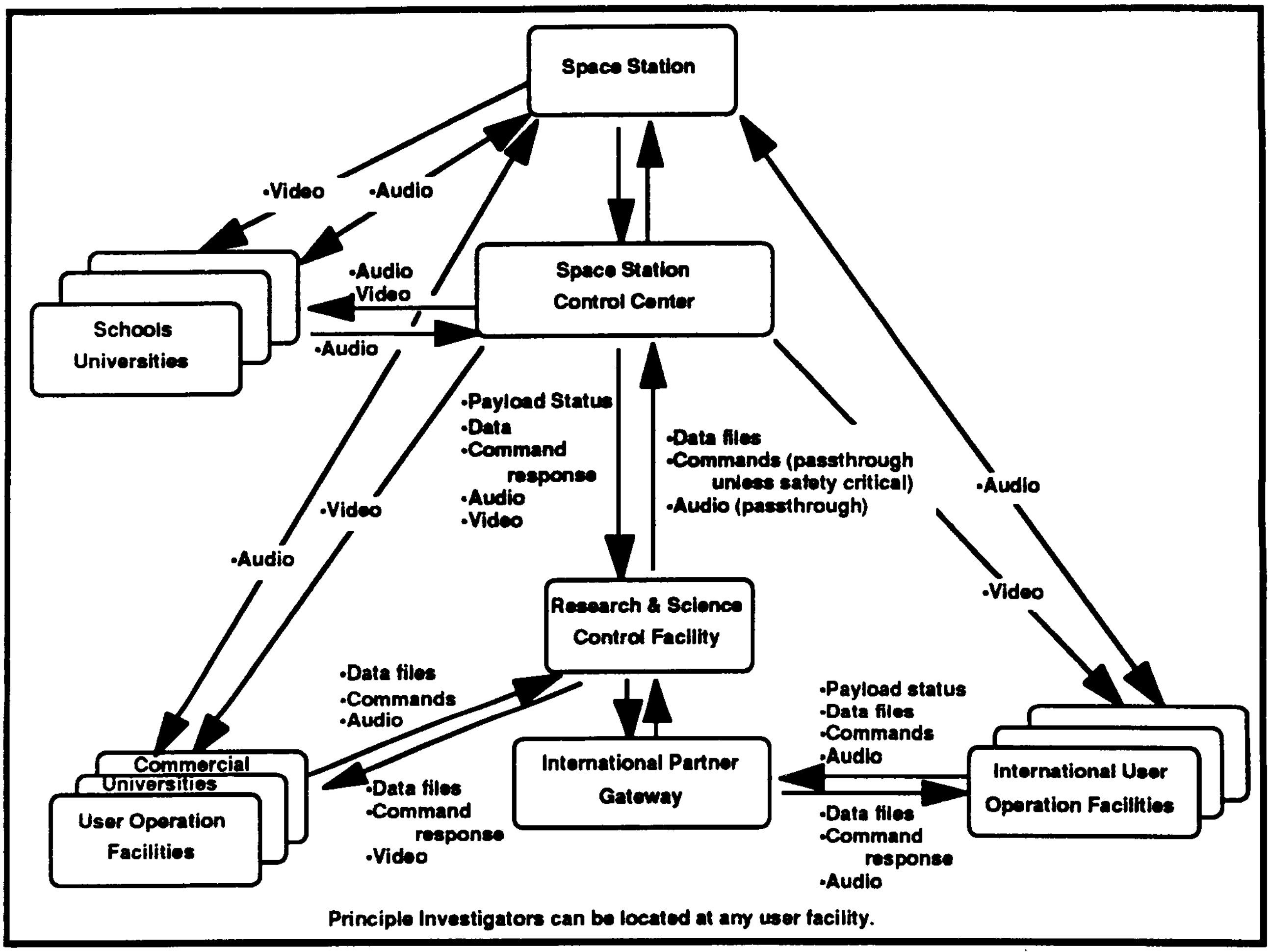


Figure 104
Research control architecture

Table 34
Payload Operations and Integration Center team reductions

Payload Operations and Integration Center			
Untended Space Station		Human Tended Capability	
Previous	21 people/3 shifts	Previous	29 people/3 shifts
Proposed	12 people/3 shifts	Proposed	18 people/2 shifts
			23 people/1 shift

Space Station Operations

There are four basic elements in Space Station operations: 1) command, control and direction of Space Station operations, 2) systems trend monitoring and assistance to the crew on problem resolution including support on software and hardware anomalies, 3) joint effort with the Payload Operations and Integration Center on advanced planning and on planning updates during on-orbit operations, and 4) mission management input as operations unfold and adjustment or refinement of mission objectives and priorities is required.

The Space Station Control Center is responsible for controlling and supporting system operations from the ground. It supports continuous operations of the Space Station and can also concurrently support a simulation with the Space Station Training Facility or systems testing. The testing can be with prelaunch Space Station elements at the Kennedy Space Center or with the Central Software Facility. During untended operations, uplink command and control will be exercised to manage communications and data systems, adjust attitudes, reboost the Space Station and to control environmental and pressurization systems. New technology, including expert systems, provides automated trend monitoring and systems management aids for all Space Station Control Center functions.

The Space Station operations function is analogous to the current on-orbit premission planning and flight control functions for Space Shuttle in support of a Spacelab flight. A significant difference is the Space Station's ability to survive 24 hours without ground intervention which reduces the time criticality of real-time operations. The reduction in personnel is shown in Table 35.

Training

A structured training plan, which provides an effective and systematic process, will be developed for each training phase. The training plan will be based on a detailed risk analysis which concentrates on probability versus possibility to determine the optimum failure response training profile. This is in contrast to the Space Shuttle training for both flight and ground crews which evolves around time-critical mission scenarios that involve multiple failure modes. Training can be modified or reduced considerably and will therefore be knowledge and proficiency based rather than driven by timeline and detailed procedures rehearsal. As in past programs, personnel will be trained for all time-critical procedures. The projected training cost reductions from those estimated for Space Station Freedom were made by using the decreased time criticality of real-time operations to drive an overall reduction in training requirements for the crew and ground controllers. This, in turn, allows reductions in the training staff, and in the demand on the training facilities. Reduced time criticality not only minimizes training requirements, but also allows for greater reliance on part-task training and on-the-job training for mission controller familiarization.

Training resource requirements will also be reduced by developing highly trained flight crew cadres in specialized operations areas. For example, flight assignments that feature crew cadres specializing in extravehicular activity and in robotic arm operations could greatly reduce the training workload presented by cross-training a significant portion of the total crew population.

The amount of payload training, as well as Space Station systems training, has been reduced. Because science return depends on operational accuracy, it is not proposed that payload training for the crew would be reduced below the proficiency level required to assure mission success.

Ground Processing

Once the flight cargo elements have undergone acceptance testing at the development location, they will be transported to the Kennedy Space Center for ground processing. This includes integrated testing, interface verification, servicing and launch activities. All experiment-to-rack physical integration is included in ground processing.

Table 35
Space Station Control Center team reductions

Space Station Control Center			
Untended Space Station		Permanent Human Presence	
Previous	21 people/3 shifts	Previous	36 people/3 shifts
Proposed	8 people/3 shifts	Proposed	10 people/2 shifts 17 people/1 shift

The ground processing or prelaunch and postlanding cost reductions centered on operations savings in three major areas: contractor personnel conversions to civil service, manifest adjustments and reductions in facility investments. Specific contractor tasks would be converted to civil servant with no increase in the Kennedy Space Center's civil servant ceiling. These civil servants would replace approximately 80 contractors per year and would be diverted from other programs such as Space Shuttle. The redesign Options A and C project a manifest adjustment from the Space Station Freedom baseline. These adjustments provide a cost reduction because of fewer mission build flights, a decrease to four logistics flights per year after the international flights, the slip in first element launch, and the elimination of the large pressurized logistics module. In general, ground processing activities are projected to be performed on a two-shift per day, five days per week basis through the completion of Space Station assembly. After assembly completion, processing facility activities will be scaled back to one shift per day, five days a week.

Staffing reductions were taken for international flights based on the International Partners providing "hands-on" personnel for their elements for the initial portion of the launch site processing. Because the station is a 10-year program, no major upgrades to facility systems, ground support equipment, computerized checkout equipment or data base systems were assumed. Only periodic and routine maintenance were assumed rather than a wholesale upgrade.

Smaller scale cost reductions were also identified. A combined engineering test team of development engineers and Kennedy Space Center engineers would cover testing at the factory and then at the launch site resulting in overall test and checkout staffing decreases. The operations and maintenance of the Space Station Processing Facility would be split with other programs sharing the facility. A concept has been developed to require less test, control and monitoring system applications software for nonrepetitive tasks by performing more manual tasks from the workstations. Overall reductions in processing equipment allow decreased personnel.

Sustaining Engineering

Sustaining engineering is the postdevelopment systems engineering and integration necessary to sustain the specification performance and reliability of Space Station systems. Sustaining engineering also includes configuration management and any associated procurement.

Space Station modifications and upgrades will be treated as new starts. To control cost, it is important to minimize any changes to equipment, systems or software. Space Station modifications and upgrades will be implemented only for safety or for improving the Space Station's ability to support inflight research capability.

A significant departure from the traditional sustaining engineering model is recommended to reduce resource requirements during the mature operations phase of the station program. This approach would avoid a costly carryover of prime contractor, subcontractor and vendor personnel into the operations phase. The sustaining engineering force from the development contractors is phased out when design and development is completed with the possible exception of a few key personnel who would be under retainer-type contracts.

The normal sustaining engineering function will be replaced by a small cadre of system experts located at each development center, to support Space Station operations. This cadre of civil service personnel would be selected on the basis of development program experience. This cadre will in most cases have assignments on other development projects but will be available to consult on Space Station engineering issues. This cadre of experts also forms the core force of the Space Station Anomaly Team which will be activated to provide support for the Space Station Control Center Team in the event of malfunctions. The Space Station Anomaly Team is available, on call, to provide information to either the ground or flight crew as conditions warrant. This team has the capability to work problems, calling on systems experts from both NASA and contractors as necessary. All design documentation, analyses, etc., will be provided to this group.

Flight software sustaining engineering will consist of a limited code maintenance capability.

This capability will consolidate all flight software activities under a single contract and will resolve software discrepancies on a priority basis.

The operational environment supported by this concept uses a "build it, launch it and move on to the next project" philosophy. The Space Station configuration that is in orbit at the start of operations is the same as that expected to be in orbit after 10 years (and extendible to 15 years). While critical systems will continue to be two-fault tolerant in this scenario, the program expects noncontinuous operations or a powered-down, safe mode for occasional periods because of contingencies or corrective maintenance.

Engineering test articles or testbeds which are representative of actual flight systems will be maintained to assist the Space Station crew in troubleshooting on-orbit anomalies, in supporting hardware integration for maintenance and preplanned program improvements, and in assisting the Space Station Anomaly Team in responding to emergency situations.

Integrated Logistics

The cost reductions for Space Station integrated logistics result from the elimination of the duplication of functions, more efficient repair and maintenance processes and risk-managed spare reductions. This concept consolidates and eliminates duplication of management and sub-function elements such as facilities and inventory management. It achieves optimum synergy of resources and expertise in Space Shuttle, Spacelab, and other payload programs. This synergy is achieved through the implementation of a Logistics Operations Management Center at the Kennedy Space Center which would be the lead center for logistics. The Logistics Operations Management Center will integrate the functions, capabilities and facilities to optimize full logistics support to the Space Station program elements and support the incremental transition of overall logistics operations from the development organizations.

Maintenance and repair costs are minimized by a combination of accepting longer repair timespans, establishing a maintenance and repair capability at the Kennedy Space Center which reduces costs of unique test equipment, documentation and training, and using original equipment manufacturers or other certified industry repair resources.

Initial spare procurements will be based on a priority order with Space Station and crew survival, ground processing criticality and sufficiency level as key criteria. The logistics approach also defers the follow-up procurement of replenishment spares and repair parts to post-fiscal year 2000, and minimizes staffing support for logistics.

Facility Support

To reduce facilities and operations support systems costs, multiprogram common support is being pursued wherever practicable. The Space Station Control Center, the front end data processing and the major trajectory and flight planning systems will have systems in common with Space Shuttle.

Ground processing and logistics facilities will make maximum use of Spacelab and payload capabilities already in place. Major initiatives are underway to reduce cost through the consolidation of test, verification and training facilities.

The Space Station Control Center facilities savings are based on a slip in first element launch; a reduction in the number of operating positions and workstations; a reduction in the round-the-clock ground data systems support; and a reduction in overall requirements on the facility to support nonmission activities such as simulations, network tests and system testing. In addition, facility maintenance and operations support costs are reduced through consolidation with Space Shuttle and Spacelab program support. Use of commercial off-the-shelf software in development of all Space Station operations facilities reduces development and recurring operations costs.

A significant reduction in program costs is the convergence of the Space Station Verification and Training Facility and the Central Testing Facility into a single architecture that services the needs of both the engineering and training communities. This single facility for both training and avionics sustaining engineering would require only one set of sustaining and maintenance personnel. The assessment has shown that the number of the full-task simulation rigs can be reduced.

The other major consolidation involves moving the Space Station mockups to the simulator facility. This concept will save development of separate crew stations for the Space Station

Verification and Training Facility and will reduce the total number of crew stations for the program by one.

For Option C additional reductions were possible due primarily to additional synergism with the shuttle and Spacelab program systems plus the fact that the option does not launch any assembly flights during the 1994 through 1998 costing window reducing the training and operations preparation buildup. The steady state operations costs run about twenty percent less for Option C. Commonality in avionics systems between shuttle and Option C resulted in allowing one shuttle training base to be converted to station use, reduced need for new control center architecture for payload and systems operations and allowed significant credits to be applied in sustaining engineering and logistics spares and related test facilities both at development sites and reduced complexity at the ground processing site. Option C also uses significantly less flight software, which results in reduced software maintenance activity.

Operations Development

Significant cost reductions in the development budget were achieved by consolidation of the payload and mission operations training facilities and by a similar consolidation of control center facilities. Further development savings were achieved through the convergence of the avionics and test facility with the training facility. In addition to these savings in the Space Station budget lines, the phasing of related activities in the Space Shuttle and Spacelab programs can result in parallel savings in those program budgets.

The cumulative operations and development cost savings through fiscal year 2000 resulting from the Station Redesign Team effort are summarized in Table 36.

Table 36
Operations cost reduction

Cumulative Operations Cost Reduction Through FY 2000			
Operations Functions	Percent of Program Operating Plan 92-1 Baseline Costs	Percent Reduction from the Baseline by Function: Options A/B	C
Mission Operations and Payload Operations	35	38	47
Sustaining Engineering	18	65	80
Logistics	19	51	76
Operations Ground	7	44	61
Management and Integration	<u>21</u>	66	66
	100		
Operations Development	Percent of Program Operating Plan 92-1 Baseline Costs	Percent Reduction from the Baseline by Function	
Mission and Payload Operations	25	38	

Management

Introduction

Current Management and Contract Structure

The responsibilities for the Space Station Freedom Program are distributed among the Associate Administrator for Space Systems Development, the Space Station Director (Level I), the Space Station Freedom Program Office (Level II), and three NASA center project offices (Level III) (Figure105). The Space Station Freedom Program Office, located in Reston, Virginia, has overall management and integration responsibility for the program. Grumman Aerospace Corporation is the Level II Space Station Engineering and Integration Contractor and is responsible for providing level-of-effort support to Level II for analysis and verification activities, requirements definition and design integration.

Three NASA centers have been designated as work package projects, each using a different prime contractor. Each center is responsible for managing the delivery of the flight elements and/or the distributed systems for its respective work package. Each work package contractor is responsible for the development, integration, testing and delivery of its flight elements and distributed systems.

Marshall Space Flight Center, manages Work Package 1, awarded to Boeing Defense and Space Group. Boeing is responsible for the laboratory, habitation and logistics modules, including life support systems and parts of the connecting nodes.

Johnson Space Center, manages Work Package 2, awarded to McDonnell Douglas Corporation. McDonnell Douglas is responsible for the integrated truss assembly, mobile transporter, airlock for extravehicular activity, communications, data management system, guidance, thermal control, solar array movement, propulsion and ground-training systems.

Lewis Research Center, manages Work Package 4, awarded to Rocketdyne Division, Rockwell International. Rocketdyne is responsible for the power system, including solar arrays, batteries and power distribution equipment.

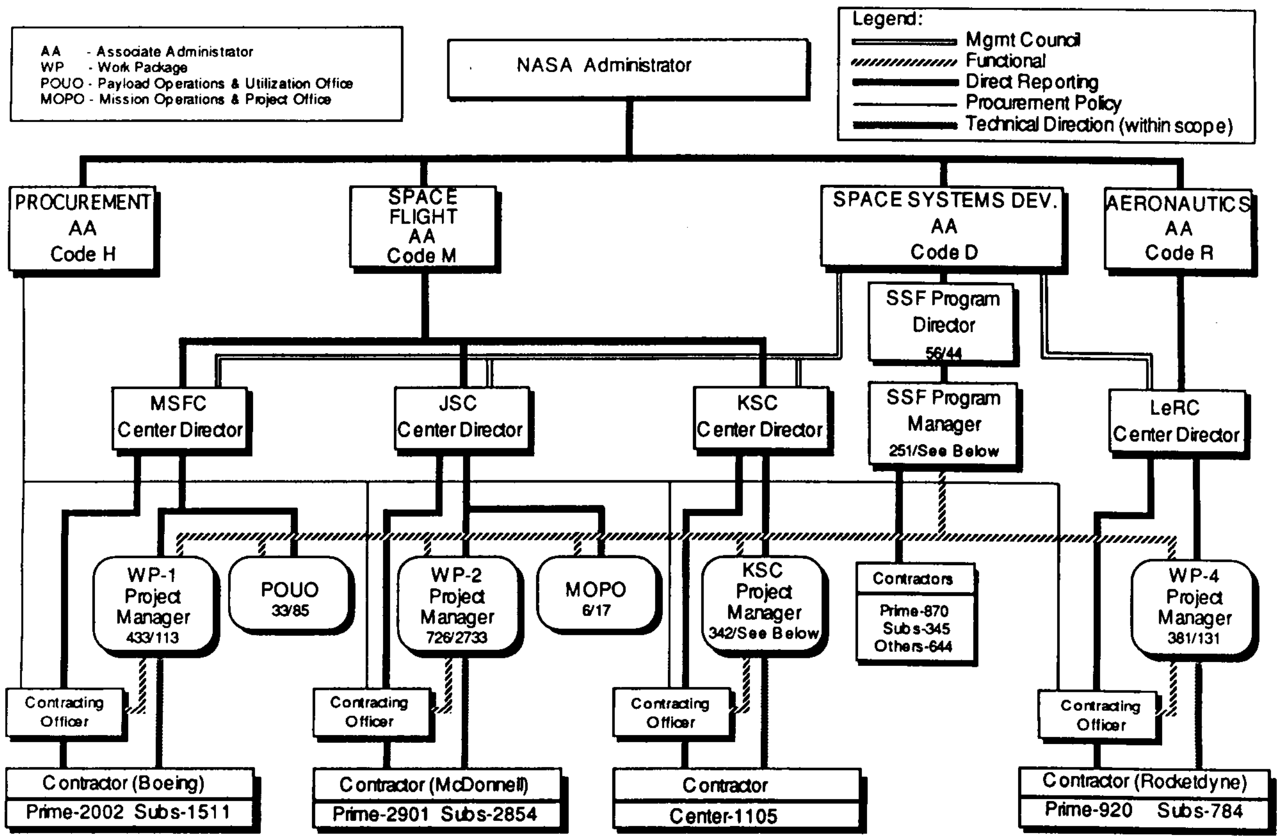
There are over 100 other NASA contracts providing development and level-of-effort support for crew training, mission design and operations, and performing numerous studies in support of Space Station systems and processes.

The Management Challenge

The Station Redesign Team was tasked to develop new management approaches for each of the three design options and to model the cost savings associated with the management changes.

The basic problem to be solved in Space Station management is to develop a set of management structures and processes that is efficient enough to execute the program. Efficiency, which is the time-money rate at which technical content is being accomplished, is not presently at or near the point of bringing the overall Space Station Freedom Program, cost, schedule and content into balance. For example:

- Current Space Station Freedom cost variances exceed all available reserves.
- Schedule variances begin accumulating within weeks after the schedules are re-baselined.
- Decisions cycle through multiloop project and program forums and once made, are frequently re-visited, or simply not implemented due to their difficulty or cost.
- The large number of people on the program with overlapping responsibilities makes accountability unclear.



TOTAL NASA	2228
TOTAL CONTRACTORS	17059
TOTAL PROGRAM	19287

Figure 105
Current Space Station Freedom management structure

- The turf issues created by this overlap impede progress rather than promote it.
- There are integration areas still unaccounted for in the contract structure of the program.

Moreover, there are extensive efforts applied to integration that are not fundamentally affecting the development products. Requirements management, for example, is applied at the Space Station Freedom Program level on documents for which the development contractors do not have responsibility. NASA requirements changes that do reach the prime contractors frequently do not reach the subcontractors in a relevant time frame. Program experience from the past several years has shown that the time to establish and distribute requirements to all product developers (one to two years) is longer than the budget period that resets some of the requirements.

Space Station Management Issues

To identify causes of the Space Station Freedom management problems the Station Redesign Team conducted extensive interviews with people at all levels of the Space Station Freedom Program, center directors and center personnel, International Partner representatives, senior contractor managers as well as outside experts. The following causes were identified:

Budget Instability and Resultant Redesign

Budget stability has been a hallmark of successful Government programs, but has been difficult to establish on the Space Station Freedom

Program. Budget instability was aggravated by an initial optimistic costing of the program. This led to subsequent redesigns, which led to further instability when predicted savings were not realistic.

Senior Management Instability

During the first four years of the program, 1984-1988, when critical decisions were made with respect to international agreements, work package content and system definition, there were five different program managers. This instability created excessive reviews of prior decisions.

Complicated Interfaces and Distributed Integration

The Space Station Freedom design has many highly distributed systems. Space Station Freedom partitioning into institutional work packages, as opposed to deliverable launch packages, has made the interfaces complex and unstable. NASA is currently responsible for system integration, however the overlap and gaps between work package and program level responsibilities hampers NASA's ability to perform integration effectively.

Excessive Levels of Management with Unclear Lines of Authority

The multiple levels, lack of clarity in lines of authority and overall size of the existing organization are illustrated in Figure 105. The current system institutionalizes and geographically separates three "levels" of management. The Space Station Freedom Program Manager has no direct control over the three prime contracts; the three work package managers who control these acquisitions are geographically dispersed and report to the center directors. The work packages represent an institutional layer of management that has been inserted into a program office structure.

The multiple layers of management have resulted in a large, highly layered NASA team of approximately 2300 civil servants, interacting with and "helping" the contractor. This has resulted in poor communication and a proliferation of engineering working groups, panels and boards. The structure and size of the NASA management team drives the contractor workforce in two ways. First, the contractor establishes layers of management that correspond to the government structure. Second the contractors require additional staff to answer the Government's demands created by the NASA management structure, but not required to do the job.

Management Principles and Selection Criteria

The Station Redesign Team defined the success criteria of the new management organization. The new management organization must:

Manage Cost – cost control, accountability and decision processes must be bound together; managers cannot focus exclusively on technical content.

Reach timely closure on decisions – layers of management should be minimized; managers must be empowered and accountable for timely resolution of program issues.

Establish clear accountability – each job must be assigned exactly once. Organizational growth must be controlled using clearly defined tasks.

Develop one team – this team must foster unity, work to eliminate walls between organizational units, provide incentives for cooperation, motivate trust and develop the awareness of a "shared destiny." (Note: this sense of shared destiny is necessary not only within the station program, but with the shuttle program as well.)

Establish clean and stable interfaces – this effort must partition responsibilities to simplify technical and management interfaces.

Recommended Management Organization

Based on the identified problems and the selection criteria, the Station Redesign Team proposes a new management organization. The following recommendations of these models apply to any of the configuration options and are location independent.

- Build one NASA team combining project and program levels into a dedicated program office with a core line management team that reports directly to the program manager.
- Build a highly effective team of demonstrated performers; establish a direct reporting path to the program manager.
- Consolidate budget authority and overall responsibility and accountability for the program with the program manager.
- Consolidate all of the contracts within the program office and negotiate to a single prime contractor. This is discussed in detail in the Acquisition Strategy portion of this report.
- Utilize integrated product teams, following concurrent engineering practices, who are responsible for the design, development, safety, quality assurance, verification and on-orbit check-out of launch packages.
- Limit the center institutional support (matrix support) to in-line tasks or facilities in well-defined areas where it is clearly cost effective.
- Locate the core management team in one place to enhance ownership and expedite decision process and communication.
- Place a skilled cadre of NASA specialists and systems engineers in contractor plants.
- Combine the Space Shuttle and Space Station Programs under a single Associate Administrator.
- Retain the international management forums agreed to in the current Intergovernmental Agreement and the Memoranda of Understanding, specifically, the Program Coordinating Committee, the Multilateral Coordination Board and the Space Station Control Board. Ensure the program manager is given both the responsibility and authority for implementing an effective system engineering process across international interfaces.

These management recommendations emphasize clear accountability over multiple levels of oversight. This moves NASA to a higher level of management, with a single check and balance in the system through an independent verification and validation activity.

The management recommendations are predicated on the selection of a prime contractor who is accountable for the total program performance. This includes cost, schedule and end-to-end system performance. The prime contractor manages award fee and funding to the subcontractors. The prime contractor will supply a contractor change control function which eliminates nonessential change and assures proper change preparation and coordination.

It is recommended that the core dedicated team contract, on a task basis, to the institutions for in-line tasks or facilities. This matrix effort is estimated at approximately 700-800 civil servants in all three options.

The center directors continue to act as a Board of Directors for the program. They monitor program progress and performance at a high level and ensure the program is obtaining the required support and priority at their institutions. The center directors do not, however, have implied or real line responsibility for the program. The center directors are not expected to sign the Certificate of Flight Readiness for the Space Station, but rather ensure due process is behind the program manager's final signature. The contract control and monitoring is performed by the program office with fee determination and performance evaluation of the core team the sole responsibility of the program line of management.

The new program office could be located at one of a number of sites. The term, "Headquarters program office" is used to describe the case where the program office is located other than at a center (e.g., Reston or Crystal City). The main advantage of this option is that it virtually eliminates center partisanship and creates one program team. This approach has been used successfully in industry and military programs to shift to new management and operations paradigms, but usually at the beginning of a program. Its chief disadvantage is that the skill base needed to execute the program won't be as easy to obtain as it would by using a core dedicated office located at the centers.

The term "host center" is used to describe the case where the program office is implemented at one of NASA's field centers. In order for this approach to work at a field center there must be a clear definition and understanding of roles established between the resident Program Manager and the host center director. The advantage of this approach is that the program office does not have to duplicate administrative functions, has easy access to an engineering base and has a sizable management and engineering base from which to draw some of the core team. The shuttle/station merge model described as an alternative for Option C is a modified version of the host center model in terms of its top-level reporting structure.

The term "lead center" is used to describe the case where the program office is located at a field center with the center director in the programmatic chain of command. Its chief advantage over the host center model is the probable "extra distance" the lead center director will go to ensure program success. This model is well-suited for programs that are largely contained within one center. However, the Station Redesign Team does not recommend this model for Space Station due to the large international involvement and multicenter nature of the work.

The specific choice of program office location is dependent on the configuration and acquisition option selected. In all cases, it is recommended that a sizable percentage of the core office, 20 to 30 percent, spend significant amounts of time in the field at the prime contractor and their subcontractors.

There should be, at most, one layer of management between the Space Station Program Manager and the Administrator. Because of the strong need to foster shuttle and station synergy, all of our options recommend that the shuttle and station are combined under a single Associate Administrator. For Option C, there is an alternative to combine the two programs under one program manager. In either case, there is a manager below the Administrator's level who is clearly accountable for solving combined program issues.

The most essential features of an efficient management structure are co-location and a single chain of command for direction and primary appraisal of work. If the Integrated Product Team members remain assigned to the field centers, we recommend re-examining the personnel policies to allow for direction and appraisal of work to come through the program chain of management. We highly recommend that at least three tiers of management below the program manager and all program members who control development contracts be assigned directly and formally to the program office management.

Several previous reviews, such as those conducted by the National Research Council and the Committee on the Future of the United States Space Program, have recommended that NASA establish a dedicated Space Station program office with the resources and people under the line authority of the program manager.

Core Program Office Structure for Options A and B

The proposed structure and staffing for Options A and B are shown in Figure 106. This model is based on a contracting approach that names a single prime contractor and elevates the NASA oversight to a higher level of requirements management. NASA integration responsibilities are delegated to the prime contractor. System management roles are moved from the institution into the program office where they are accountable for balancing cost, schedule and technical content.

Based on these groundrules, a core program office is recommended in the range of 300 civil servants. Approximately 700 additional civil servants would be matrixed to perform in-line tasks, manage facilities, plan and perform operations and utilization and do logistics and launch processing. It is recognized that organizational details will differ as a function of key manager preferences, however, the organizational features that represent team recommendations are summarized below:

- A single location for the core management team is emphasized. However, if some of the core team are located elsewhere, they continue to report directly to the program manager.
- In addition to the core management team the institutional skill base is utilized (matrixed) in well-defined task areas, such as vehicle operations, payload integration, launch processing, in-line tasks or facilities. This work is product-oriented and is not focused on directing or monitoring the development contractor.
- The Systems Engineering and Integration organization maintains the total vehicle requirements, which NASA manages at a higher level than in the current program. This organization man-

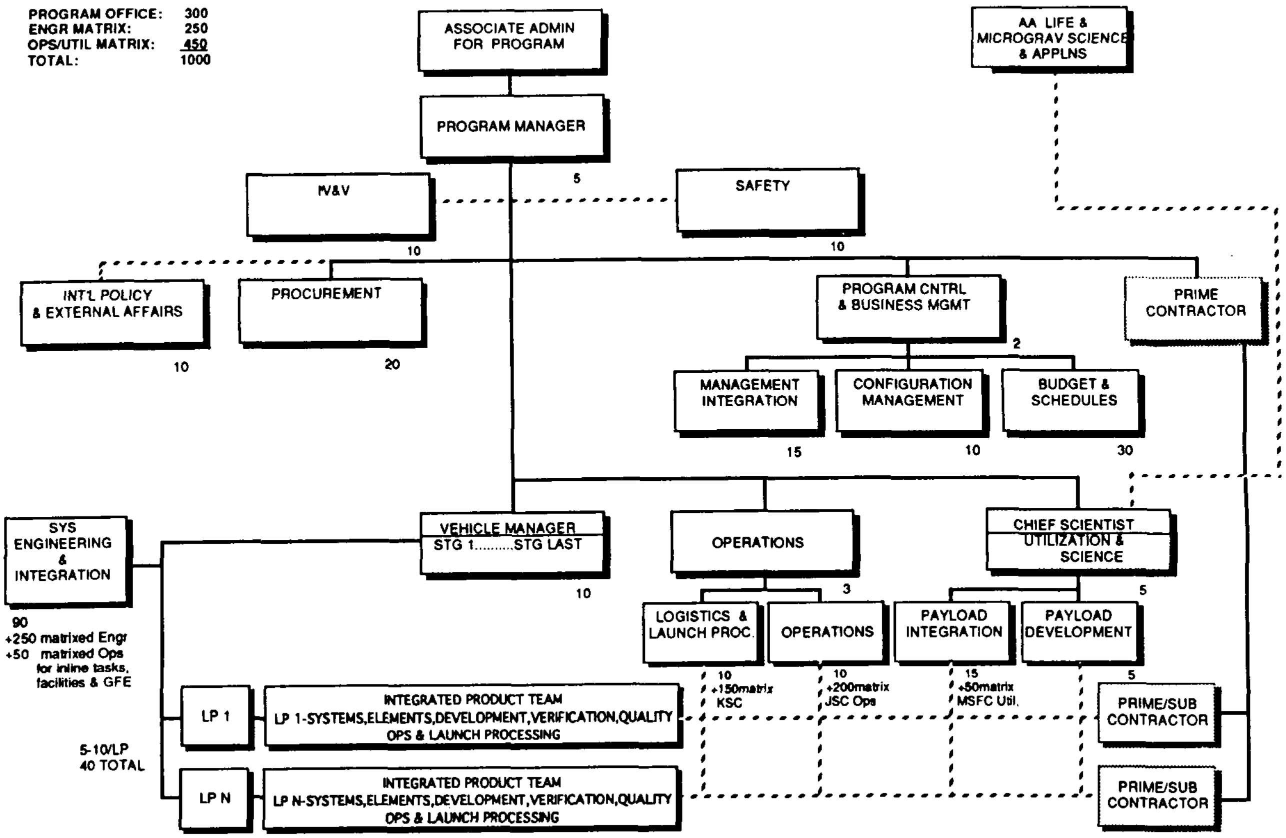


Figure 106
Proposed management structure for Option A and B

ages vehicle level analyses, phases the system architectures to each stage and allocates resources and functions to each launch package.

- The Integrated Product Teams are responsible for the functional and physical integration of each launch package. This vastly simplifies the verification program by organizing around launch packages, rather than by systems or work packages. The launch package manager is accountable for resolving any competing claims on the development activity. A feature of the organization is that it has very few layers of management between the program manager and the teams responsible for major deliverable units.
- The current role for an independent safety and independent verification and validation function is modified in this management model. The engineering and analysis associated with safety reliability and verification are in-line responsibilities of the vehicle manager. The Safety and Mission Assurance office advises the program manager, but reports directly to the Safety and Mission Assurance Directorate at the host center. The role of this office is oversight and establishment of the processes and criteria that must be followed to determine that the Space Station is safe. Independent verification and validation, and policy guidance by this group provide the check and balance of the vehicle manager's and prime contractors' efforts.
- The organization is structured to allow a smooth transition from development to operations. As each launch package becomes part of an in-flight stage, some of the Integrated Product Team members

are phased into the operations organization.

- Payload development activities are part of the utilization and science organization. The major funding for flight experiment facilities such as the furnaces and centrifuges are included in the utilization and science organization portion of the Space Station Program budget. This budget becomes the formal responsibility of the chief scientist who has a primary reporting path to the program manager, with a secondary reporting path to the NASA chief scientist or the Associate Administrator for Life and Microgravity Science and Application.
- The International Partners work with the safety office for establishing consistent safety standards and processes to which engineering activities adhere. This is different from the current environment in which Partners have separate safety criteria which are often the basis for divergence in the design. The International Partners work with the systems engineering and integration organization for defining their interfaces. As the integrated product teams form for the international launches, the International Partner work with NASA will shift to those teams. On the operations and utilization side, the Partners will participate with NASA in the vehicle operations, and utilization planning, payload integration and in the logistics and launch processing for their systems and elements.

Core Program Office Structure for Option C

Two management structures were developed for Option C. The first model shown in Figure 107, has a separate program office for Space Station and Space Shuttle under a combined program Associate Administrator. The second model, depicted in Figure 108, merges the Space Shuttle and Space Station Program under a combined program manager.

Both models share many similarities with the management approach described for Options A and B. In both approaches, a small, co-located, dedicated program office is organized using integrated product teams to manage station development. All of the station contracts are managed by this single program office. The systems engineering and integration function, the integrated product teams, the payload development function, International Partner interfaces, independent safety and verification and validation are structured the same as earlier. The additional functions needed for the Option C configuration are (1) the shuttle system integration function, which is needed for integrated launch vehicle analyses, and (2) acquisition of shuttle subsystems and components, which needs to be coordinated with several shuttle project offices. To an even larger degree than for Options A and B, Space Shuttle and Space Station synergy is critical for Option C to be successful.

For the separate station program office approach, synergy with the shuttle could be fostered by co-location of the two program managers, reciprocal program objectives in each of their job descriptions, and selecting both program managers in consideration of their potential for a strongly cooperative working relationship. It is recommended that the current Shuttle System Integration Group matrix into the station program office for performing integrated launch vehicle analyses. It will be crucial for the two programs to jointly develop a work plan covering mutual activities and needs and track against shared milestones. It is recommended that the operations and utilization functions be structured and staffed with a clear intention of merging the two programs during the operations phase.

In the second management model, synergy between the two programs is partially enforced by merging the two organizations under one program manager. In this model, it is recommended that a deputy under the combined program manager be assigned budget authority and accountability for the development of the station orbital vehicle. This added layer of management in the field is warranted by the broader span of control of the combined office. Under this Deputy for Station Development, a streamlined, single team would manage the orbital vehicle development, positioned as a direct reporting project (i.e., non-matrixed) within the shuttle and station program office. Below the Deputy for station development, the organization would be the same as was described for the separate program office. In this model, there is potential for greater leverage

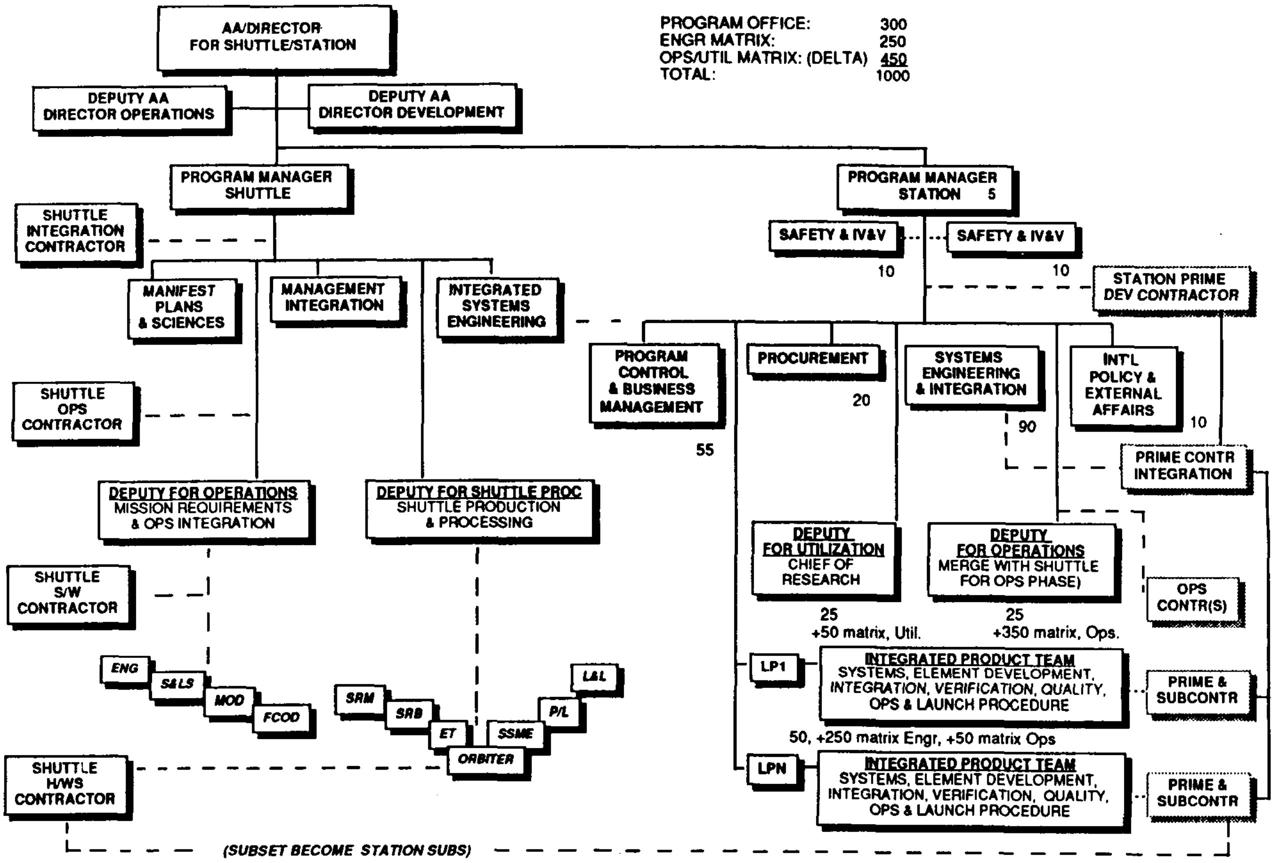


Figure 107
Separate office management structure for Option C

of existing shuttle engineering expertise that could be matrixed to the program office in specific task areas. Another feature of this model is that it combines operations and utilization for the two programs earlier in the station life cycle.

These two management models for Option C are approximately the same size as as for A and B. A core office of approximately 250 - 300 is augmented with another 600 - 800 institutional support personnel for in-line tasks and facilities. These civil service staffing levels assume that NASA manages the contractors at a high level specification and limits supporting development to critical high risk areas. The additional staffing reductions in Option C accrue if Space Shuttle subsystems are left unchanged and can be ordered from the Space Shuttle parts list. Engineering expertise is either moved into the program office for subsystem management or leveraged from the existing shuttle base of expertise.

The two management models for Option C have reciprocal strengths and weaknesses; with either model, considerable management attention will be needed to mitigate its drawbacks. The separate station program office is more conducive to promoting and reinforcing new management approaches. Changing ways of doing business will be resisted less in a separate office, than in a combined office. On the other hand, efficiency gains of a separate office can be offset by lack of synergy with shuttle. Problems between shuttle and station may percolate up to Headquarters more frequently, requiring more time and staff for resolution.

In the combined program office, synergy and conflict resolution are worked in the field. Cooperation between shuttle and station comes

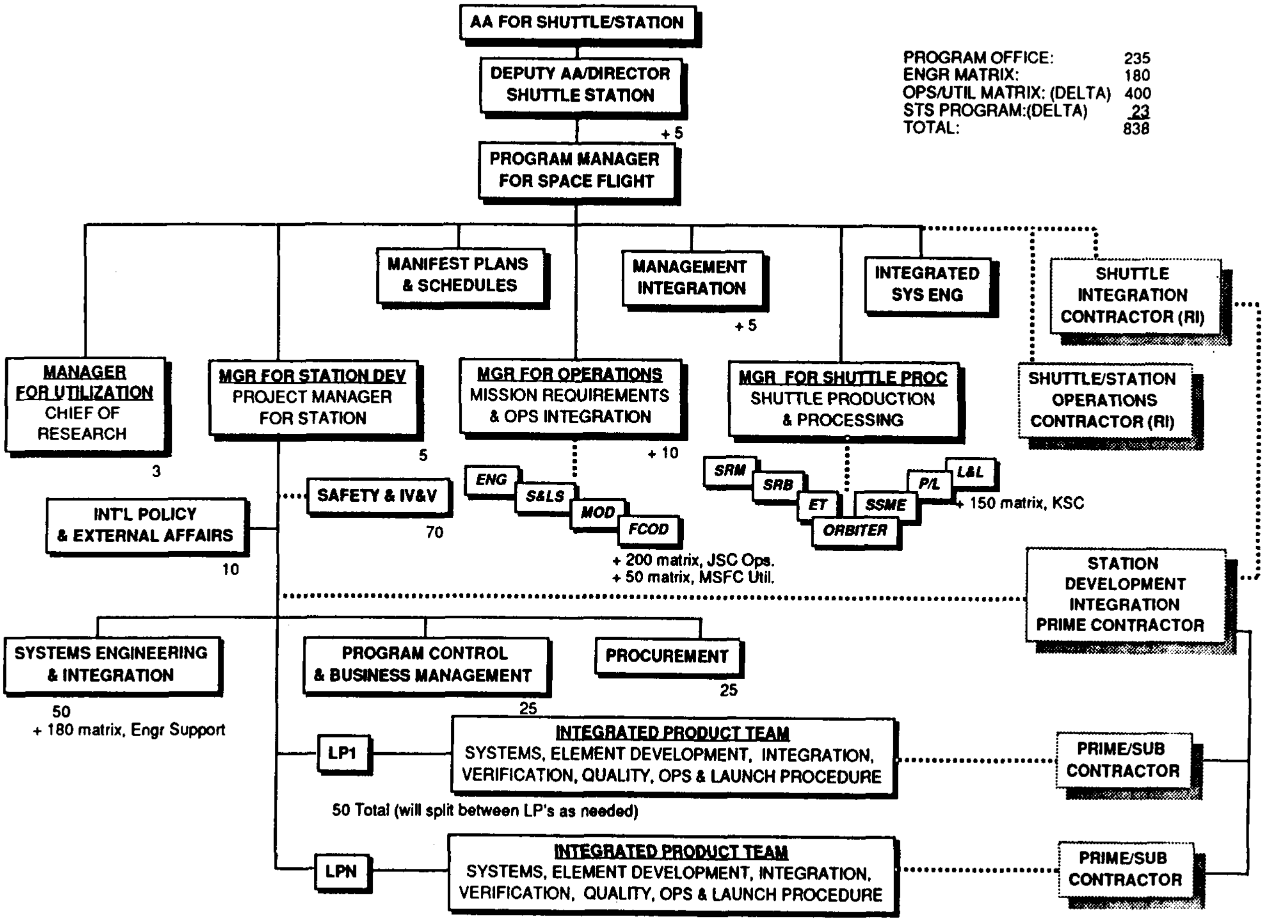


Figure 108
Combined office mangement structure for Option C

about more naturally as the organization reinforces the sense of shared destiny. On the other hand, this structure does add another layer of management underneath the Associate Administrator, increasing the potential for uncertain responsibilities and "end runs." Approximately half of the Agency's budget would be managed within this combined program office, giving it an extraordinary span of control. Finally, the existing station management structure was patterned after the shuttle; shuttle efficiency as a development organization is closer to where station is now, than to where it needs to be. In this sense, a combined office represents the more pessimistic case of management efficiency, and was the model assumed for the Option C costing analysis. If this model is implemented, additional effort and exceptional leadership will be needed to motivate and implement management improvements within the combined shuttle and station management team.

Projected Savings Due to Management Restructuring

To estimate the savings possible with a streamlined management approach we have, (1) identified specific areas of overlap, (2) modeled recommended improvements in the decision process, (3) compared metrics from other successful programs, and (4) obtained contractor estimates of the potential for savings in a more streamlined approach.

In order to understand the order of magnitude of savings that might be expected from the proposed management changes, two analyses were performed based on a nominal 1994 development budget for the current program (nominal $2.4 billion total budget). We distinguish two separate effects on management savings, (1) streamlining NASA management and working to a high level specification, and (2) consolidating to a prime contractor and using Integrated Product Teams.

Analysis #1

A parametric analysis was performed using cost reduction factors derived from other NASA, military and industry programs. Contractors estimated their overall efficiency gains in the range of 12 to 15 percent if the program were consolidated to a prime contractor and Integrated Product Teams were used. This is conservative relative to other industry experience. For example, Boeing experienced an 18 percent reduction overall on the 777 program post-critical design review after implementing a product team approach to the program. NASA estimates of the overlap in the three prime contractors was in the range of 12 to 20 percent. For this analysis, we chose a mid-value credit of 15 percent on the development and integration contracts.

In addition, an estimate was made of the ripple effect or "churn" that the large NASA team causes at the contractors. This was estimated by calibrating against comparable military programs at a major contractor. As further supporting data, wraps that are implicit in the cost estimating relationships for past NASA programs were compared to the wraps that the current station program is experiencing. Both of these approaches indicated that a 12 to 20 percent credit is possible through more efficient management. For this analysis, we chose a conservative credit of 12 percent on the development and integration contracts.

These credits are partially offset by the costs of additional fee due to moving to a single prime and additional fee to cover an incentive fee arrangement. The net percentage savings estimated on the development and integration contracts is 15 to 20 percent. Expressed as a percent of total program costs, which includes operations, this is a 13 to 15 percent savings.

In addition to direct contractor savings, a civil service credit is possible, assuming some percentage of civil servants released from the program could be applied to activities that offset other program costs, such as operations and utilization. Based on a core program office of approximately 300 civil servants, with another 700 matrixed to perform in-line tasks, approximately 1300 civil servants would be available to staff positions now anticipated to require support contractors. Depending on the percentage of placement of these personnel, additional savings in the range of two to four percent of total program costs are possible.

Analysis #2

An analysis of the possible savings in the baseline program was derived by examining specific streamlining steps as they would affect budget line items. Specific reductions included: (1) reducing NASA forums by 80 percent, (2) eliminating dual loops in the project and program review and decision process, (3) reducing the number of civil servants on the program and directing them through one chain of management, (4) managing requirements at a higher level, (5) simplifying the verification program by launch packages, (6) retaining supporting development only for in-line tasks and facilities, but not for additional "smart customer" expertise, (7) largely eliminating Headquarters and Reston contracts.

These credits were accumulated into percentage savings in the range of 10 to 23 percent for various prime and supporting development line items and 60 percent for program engineering and integration line items. Both development and operations line items were included in this analysis. Addbacks included wraps as in the previous analysis. The net credit was approximately 15 percent of total program costs. In addition, there is a potential civil service credit in the range of two to four percent, as in the previous analysis.

There is close agreement between the "grass roots" model staffing approach and the parametric approach. In both cases, the net savings, including the civil service credit, is 15 to 20 percent of total program costs. The ability to realize the civil service savings will depend on such factors as attrition and skill mix. Savings are likely to be lower in the first year due to breakage involved with schedule setback and transition to the new management model. Finally, savings may be reduced given the introduction of these management changes midway through the development phase of the program, rather than at the beginning. Considering these caveats, we would not recommend taking full credit for these cost savings up front. The savings estimated in this analysis represent targets that should be set by the redesigned Space Station management team.

Transition Considerations

A dedicated Transition Team will be established to plan for the implementation of the redesigned Space Station in terms of the redefined NASA management structure, the acquisition strategy and the associated contract terminations or descopings required by the selected redesign option.

The team should be formed soon after completion of the redesign effort and must be lead by and consist of members who will become part of the redesigned Space Station Program.

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Acquisition Strategy

Introduction and Scope

At the President's direction, the NASA Station Redesign Team has developed three options to significantly reduce the costs and to accelerate the delivery of a redesigned Space Station. The first option, Option A - Modular Buildup, makes use of much existing Space Station Freedom systems and retains the current contracts, though reduced in scope and spending levels. The second option, Option B - Space Station Freedom Derived, makes somewhat greater use of existing systems with the goal of implementing the Space Station Freedom concept in a reduced form. As with Option A, Option B retains the current contracts at a reduced scope, but the levels are not drastically reduced. The third option, Option C - Single Launch Core Station, essentially abandons existing systems and contracts in favor of a new concept which maximizes use of the Space Shuttle's capabilities and contracts. This option would require the termination of most, if not all, Space Station Freedom contracts and build a canister-type spacecraft to be placed in orbit by a single launch of a Space Shuttle-derived vehicle.

All of the options under consideration require significant changes in the level of activity expected of the Space Station Freedom contractors. Accordingly, when the President selects one of these options, NASA can anticipate that some contracts will be terminated and others modified. As a result, the current Space Station Freedom contractors will, of economic necessity, lay off employees, close plants, and cancel subcontracts. Depending on which option the President selects, the layoffs and plant closings at the prime and subcontractor levels vary from substantial to near total in magnitude. Ultimately, however, the primes and subcontractors, not NASA, must make these business decisions.

Regardless of the redesign option under consideration, NASA will use a hybrid fee approach combining the features of a cost-plus-award fee contract with fee for performance incentive milestones in order to place increased emphasis on schedule, cost control and technical performance and to promote maximum effort on the part of the contractor to achieve successful performance of the redesigned Space Station after delivery and acceptance.

Background

Space Station Freedom Program Responsibilities

The Space Station Freedom Program Office, Level II, located in Reston, Virginia, has overall management and integration responsibility for the program. Grumman Aerospace Corporation is responsible for providing level-of-effort support to Level II for analysis and verification activities, requirements definition and design convergence integration support. The current estimated value of this contract is $1.2 billion.

Marshall Space Flight Center, Huntsville, Alabama, manages Work Package 1, awarded to Boeing Defense and Space Group. The contract has a current estimated value of $3.1 billion. Boeing is responsible for the laboratory, habitation and logistics modules, including life support systems and connecting nodes.

Johnson Space Center, Houston, Texas, is responsible for Work Package 2, awarded to McDonnell Douglas Corporation. The contract has a current estimated value of $5.1 billion. McDonnell Douglas is responsible for the integrated truss assembly, mobile transporter, airlock for extravehicular activity, communications, data management system, guidance, thermal control, solar array movement, propulsion and ground-training systems.

Lewis Research Center, Cleveland, Ohio manages Work Package 4, awarded to Rocketdyne Division, Rockwell International. The contract has a current estimated value of $2.3 billion. Rocketdyne will provide the power system, including solar arrays, batteries and power distribution equipment.

In addition to the four primary Space Station contracts, there are numerous other NASA prime contracts providing development and level-of-effort support for crew training, mission design and operations, and performing numerous studies in support of Space Station systems and processes.

Current Integration Role

NASA is solely responsible for program integration. Level II has the overall integration responsibility. Level III has the responsibility for managing the delivery of the integrated and tested elements and the distributed systems. All prime contractors have responsibilities for integration support. Grumman is responsible for program level integration support for master schedules, requirements, planning and verification. Work package contractors are responsible for the integration associated only within their work package elements and systems.

The multiple contract arrangement and NASA's integrator role have led to the development of an intersite deliverable list containing in excess of 3,000 items. Work package contractors provide their intersite deliverable items for inspection and acceptance by NASA. These intersite deliverable items are then provided to the receiving work package contractor as Government furnished equipment. Work package contracts currently have no specific provisions for integration of systems between the work packages.

Basic Acquisition Strategy for the Redesigned Space Station

General Approach

The acquisition strategy developed for the redesigned Space Station will strengthen the integration process by removing NASA from the prime integrator role, significantly reduce the number of interfaces, and complement a streamlined management structure.

To that end, the acquisition strategy provides for selection of a single prime contractor from among the existing development contractors. Full integration responsibility will be transferred from NASA to the selected prime contractor. In addition to its own systems development, the single prime contractor/integrator shall now be accountable to NASA for the entire program.

To the maximum extent possible, NASA will retain and utilize the existing Space Station contracts. All remaining contractors (work package, other primes and selected subcontractors) will be assigned as first tier subcontracts to the single prime contractor-integrator, as needed. The newly assigned subcontractors shall be responsible for the systems development effort under subcontract and for providing integration support to the single prime contractor. The single prime contractor/integrator shall be responsible for managing the subcontractor's performance.

NASA will issue change modifications to the single prime contractor/integrator to restructure and modify content to reflect the redesign option requirements, to add the integration role and accountability and to assign the necessary subcontracts. The single prime contractor/integrator will modify subcontract content for the redesign option requirements.

Competition

While law and regulation recognize a strong bias in favor of the competitive award of Government contracts, the benefits of competition are most pronounced where, unlike here, the competition is held at program outset. Here, several factors distract from the presumed benefits of competition. The Space Station program is an ongoing program with a large, skilled workforce in place. The competitive process would be time consuming, probably taking in excess of 12 months to complete. A 12 month hiatus to the existing contracts would prove to be both very disruptive and expensive. Contractors involved in the competitive process would lose focus on the work they currently have under contract and teamwork would undoubtedly be eroded. Each current contractor would be forced to choose between suspending work and losing skilled workers while the competition is in progress or continuing to perform work that might not be needed or appropriate. In short, a full-and-open competition would be costly due to schedule delays and wasted efforts. Current procurement law does permit sole-source contracting when an agency head determines, after notice to Congress, that such an approach is in the best interest of the Government. Here, the redesign team believes that such an approach would be more efficient, expeditious, and less costly. It also believes that the unique technical aspects of each option and the existence of systems and expertise applicable to each option would permit an informed selection of the best prime contractor/integrator. Therefore, we strongly recommend that whatever option is chosen, the selection of the single prime be done on a noncompetitive basis.

Option Specific Strategy

The general acquisition approach discussed above is applicable to each redesign option. The redesign options differ only in the requirements to be purchased. The acquisition approach for Options A and Option B focuses on the realignment and reduction of the Space Station Freedom development contracts under a single prime contractor/integrator. The resulting contract with the single prime will be for design, development, full integration, test and delivery of a functional redesigned Space Station.

Option A - Modular Buildup Concept

The Option A design repackages the Space Station Freedom baseline approach into a modular buildup process assembled in four major phases. Option A utilizes, but simplifies and reduces, the baseline Space Station Freedom system. All work package contracts are retained for restructure as follows:

Work Package 1	Reduced quantity of modules and nodes; simplifies the life support system.
Work Package 2	Limited number of truss sections used; major simplification of the data management system; simplifies the thermal control system and communications subsystem.
Work Package 4	Restructures the power system by modifying the solar array and battery systems.

Option A consists of two variations. Option A-1 uses the Bus-1 for guidance, navigation and control, attitude control and propulsion. NASA will obtain the Bus-1 under an interagency agreement from another Government agency. The Bus-1 will be provided as Government furnished property to the selected single prime contractor/integrator. Option A-2 uses the current baseline subsystems for guidance navigation and control, attitude control and propulsion in place of the Bus-1.

Option B - Space Station Freedom Derived

Option B makes greater use of the current baseline systems than Option A. Like Option A, this option retains all of the work package contractors modified as follows:

Work Package 1	Retains the early laboratory and habitation modules and the logistics elements, with connecting nodes arranged differently than the current baseline; minor changes made to the life support systems.

Work Package 2	Eliminates one truss section (P2); significant reductions made to the data management system and to the communications and tracking subsystem.
Work Package 4	Retains the power system as currently contracted.

Option C - Single Launch Core Station

Option C essentially abandons the Space Station Freedom systems in favor of a concept which maximizes the use of the Shuttle's capabilities and contracts to build a canister-type spacecraft to be placed in orbit by a shuttle-derived vehicle.

As for the previous redesign options, the acquisition strategy for Option C-1 is to select a single prime contractor with full integration responsibility for the single launch core station.

Option C uses Shuttle capabilities to the maximum extent:

a. Shuttle elements: Use the existing contracts (without modification) for the solid rocket boosters, external tanks, and shuttle main engines.

b. Shuttle System Systems: Modify the existing Shuttle contract to acquire orbiter aft fuselage, external tank interface and needed orbiter systems (data management system, communications and tracking, propulsion, external thermal control subsystem).

c. New Systems: Consists primarily of the pressure vessel and outfitting. The Station Redesign Team is considering different options to build the pressure vessel. One approach is to use the existing capability at the Michoud Facility using the same manufacturing techniques as for the external tank. This approach appears to be cost-effective and possesses the least technical risk. Another approach is for the Government to build the pressure vessel in-house at the Marshall Space Flight Center. Other approaches using the existing capabilities on the Space Station program to build the pressure vessel are being studied.

d. Space Station System Systems: Use Space Station systems and subsystems where practical – life support systems, manned systems, guidance navigation and control, and internal thermal control subsystem.

Under this option, essentially all of the existing Space Station Freedom contracts are terminated. The single launch core station uses 47 percent of the systems and components from the Space Station Freedom program. Program emphasis would be to establish ownership by all parties and facilitate an early and clear definition of requirements and a program plan.

Operations

The prime contractor integrator for the Space Station systems development would be responsible for all Space Station mission and payload operations, including a sustaining engineering capability and spares for the Space Station program through completion of the development contract. Within one and one-half or two years prior to contract completion, a single operations contractor could be acquired on a competitive basis. Sustaining engineering would shift to the new operations contractor after a suitable phase-in period. The responsibility for providing spares could remain with the systems development prime contractor.

An alternate acquisition approach would be to retain the systems development as a subcontract to the operations contractor for critical sustaining engineering support and spares.

Assured Crew Return Vehicle

All three redesign options contain the requirement for an assured crew return vehicle. The prime contractor integrator would be responsible for the assured crew return vehicle development. The assured crew return vehicle contractor would be a first tier subcontract to the prime integrator.

Basic Contract Type and Fee Structure Approach

NASA intends to negotiate a hybrid fee approach with the prime contractor integrator. The goal is to combine the subjective features of a cost-plus-award-fee contract with the more objective features of performance incentive milestone fee. This fee approach provides NASA with maximum flexibility to evaluate contractor performance levels and the conditions under which those levels are achieved, to adjust the evaluation quickly to reflect changes in NASA management emphasis and concerns, and to focus fee on readily identifiable and measurable specific events.

Award Fee

The award fee process should complement the redefined management philosophy where award fee is considered the program manager's key tool and an integral part of the management system, not a separate process.

Award fee will be used for the routine, periodic evaluation of the prime contractor's ongoing performance. The award fee evaluation periods shall be six months in length. NASA shall use mid-term evaluations to provide feedback to the contractor on NASA's assessment of the quality of performance. NASA shall provide areas of emphasis to the prime integrator prior to the start of each evaluation period to emphasize those items considered important during the period.

Schedule, cost and technical considerations will be included as evaluation factors. Also, award fee evaluation factors will be tailored to recognize the single prime integrator concept and its implementation as well as operations, and to emphasize subcontract management, among other issues.

Performance Incentive Milestones

In addition to the award fee process, performance incentives shall be included to motivate the prime integrator with increased fee for attaining schedule, cost and performance levels more beneficial than expected for a given milestone or event and penalize the contractor through reduced fee for less than expected levels.

Performance incentives shall be structured to allow for both positive and take-back fees based on systems performance after delivery and acceptance. To do this, the contract shall establish minimum performance requirements. If performance exceeds the minimum requirements, then the contractor may earn all or part of the milestone fee negotiated for that event. If performance is less than minimum requirements the Government may take back all or part of the negotiated milestone fee not to exceed earned award fee to date.

Contract Terminations and Reductions in Content

Depending on the redesign option selected, contract terminations and reductions will vary from substantial to near total in magnitude. Option B contains the lowest amount of termination costs while Option C has the highest termination costs. The termination costs for Options A-1 and Option A-2 fall between these extremes but closer to the termination costs for Option B.

Transition and Implementation

A dedicated Transition and Implementation Team will be established to take ownership of the redesigned Space Station and to manage the Space Station Freedom program, while planning for the implementation of the redefined NASA management structure, the acquisition strategy and the associated contract terminations or descopings required by the selected redesign option.

The team will be formed soon after completion of the redesign effort and must be lead by and consist of members who will become part of the redesigned Space Station program.

At the beginning of the transition period, soon after the President selects a redesign option, certain events must occur. The selected management option must be implemented and the single prime contractor/integrator must be selected. NASA and contractor management must understand the redesigned program and what is expected to ensure success. NASA organizational changes must be implemented to accept the redesigned station program. The timing of these decisions will effect the timeliness of overall program implementation. If the decisions and implementation of the management structure are poorly timed, then termination costs will increase and the effectiveness of the transition will decrease.

Acquisition Issues

The recommended acquisition approach depends on NASA receiving authority to implement on a noncompetitive basis. The acquisition approach will need to be significantly adjusted if the management approach differs from that recommended in this report.

The hybrid fee approach must be sufficient to properly motivate the contractor in each period and must be results oriented. Further, the redefined management philosophy must support the view of using the fee approach as a primary management tool.

International Partners' Evaluation

Background

In 1988, an *Agreement Among the Government of the United States of America, Governments of Member States of the European Space Agency, the Government of Japan, and the Government of Canada on Cooperation in the Detailed Design, Development, Operation and Utilization of the Permanently Manned Civil Space Station*, was signed. This Agreement established a long-term international cooperative framework among the International Partners in the Space Station Freedom program. This Agreement specifically defines the nature of this partnership, including the respective rights and obligations of the Partners in this cooperation. Subsequent Memoranda of Understanding between individual cooperating agencies provided detailed guidance in implementation of the provisions of the agreement. A separate Memorandum of Understanding between NASA and the Italian Space Agency established a bilateral cooperative program covering the detailed design, development, operation and utilization of additional elements. The following sections are the evaluation and assessments of the International Partners and the Italian Space Agency.

European Space Agency Technical Assessment

Introduction and Background

The European Space Agency, having been invited to participate in the international Space Station Freedom program by the United States in 1984, is developing the Columbus Attached Pressurised Module, to be launched by the United States Space Shuttle and to be attached to the United States core Space Station. The Attached Pressurised Module, providing a shirt-sleeve environment for life, materials and biological research, will contain 20 equivalent rack volumes for experimenters, 46 percent allocated for the sole use of United States users and three percent for Canadian users. As part of the arrangement documented in the International Governmental Agreement on Space Station and Memorandum of Understanding between ESA and NASA, ESA also provides a polar orbiting platform, to be launched on an Ariane launch vehicle in 1998, for Earth sciences. The Memorandum of Understanding also has provisions for an earlier envisioned, ESA operated, free flyer (the development of which has been deferred) and for the use of non-Space Station facilities, such as the Ariane launch vehicle and the European Data Relay Satellite. The development of the Attached Pressurised Module is continuing pending the uncertain outcome of the Space Station redesign activities at NASA.

General

ESA's option assessment is primarily based on the international "Operational Ground Rules," which came into force on March 26, 1993. Lack of a unified set of requirements has made the assessment and comparison of options rather difficult. Also, cost and complexity reductions that were not uniformly applied to all options are identified in the report with the request to equally apply these to all options for better comparison.

The evaluation contained in the subsequent chapters is based on the final presentations and supporting data provided through May 20, 1993. A last review of the final option descriptions, contained in the redesign options part of this report, has not identified changes in the Option A and B technical definitions. However, the Option C description contains last minute technical updates in areas critiqued earlier by ESA. These changes are largely unsubstantiated in the report and are not reflected in corresponding updates to affected resources (mass and power budgets) and can therefore not be considered credible improvements that enhance the option's assessment.

Typical examples are:

- The stated increase in thermal rejection capability from 44 kW to 64 kW
- The incorporation of the Space Station Freedom fire detection and suppression harware to enhance the fire detection and suppression capability
- The stated commitment to provide the Columbus Attached Pressurised Module with regulated power (120 vdc plus or minus 3 volts)
- The addition of the "power module" to the forward end of the vehicle as a "growth" potential to provide additional power and heat rejection for the International Partner modules.

The revised weight summary provided in the report confirms the ESA opinion that the mass margin allocated for a program at this stage of maturity cannot be considered acceptable. Likewise, the allocated system housekeeping power budget of 11 kW, compared to 16 kW for the other options, also cannot be considered a credible number.

Orbit Inclination

For all three options being evaluated, the baseline inclination has been set to 28.8 degrees, with a baselined usable launch mass of 31,800 pounds. The advanced solid rocket motor, which would increase the usable launch mass to 43,800 pounds, will be available only in the year 2000, at the earliest.

With an Attached Pressurised Module baseline wet mass roughly equivalent to Space Shuttle performance, and a baselined partially outfitted (with payloads) design mass of 37,479 pounds (17,000 kilograms), the Columbus Attached Pressurised Module with initial payloads cannot be launched without advanced solid rocket motors, which are currently committed in the baseline for the Attached Pressurised Module launch.

The Attached Pressurised Module, if launched prior to the availability of the advanced solid rocket motor (1999 and 2000), would have to off-load all its initial payloads in order to be compatible with the "new" Space Shuttle performance, or ESA would have to accept a launch slip from four to seven months, depending on the option selected. A cost and benefit trade will have to be initiated after NASA has established a new programme baseline.

For the 51.6 degree inclination case, without advanced solid rocket motor and without a new aluminum lithium tank, the resultant available launch mass is 19,000 pounds. Even totally off-loading all payloads and reducing the Attached Pressurised Module to half-size, with a capability of only seven International Standard Payload Racks instead of 20 as per baseline, the Attached Pressurised Module wet mass would still exceed the available launch capability by about 6,000 pounds.

To retain the Attached Pressurised Module baseline, both the advanced solid rocket motor, as well as the aluminum lithium tank would have to be available (launch capability of 38,500 pounds).

The addition of the aluminum lithium tank (launch capability 26,500 pounds) only, will not be sufficient for an Attached Pressurised Module baseline launch and will require a significant downsizing of the Attached Pressurised Module. The advanced solid rocket motor alone, will make the impact comparable to the 28.8 degree inclination case without advanced solid rocket motors (launch capability 31,000 pounds).

Dual Access to Space Station

There is only one proclaimed reason for the high inclination orbit of 51.6 degree, namely dual access to the Space Station from Russia for times when the Space Shuttle is not available. Dual access is for regular assured crew return vehicle (Soyuz) replacement, for normal logistics upload and for crew exchange.

Launching from Kourou, French Guyana, by Ariane for Soyuz replacement and normal upload logistics into the baseline 28.8 degree inclination orbit avoids the constraints in upload mass and Space Shuttle upgrading and the associated extra cost of the high inclination orbit. Ariane V, man-rated launches, in conjunction with the European assured crew return vehicle, are currently planned to be available in 2001.

Payload Accommodations

All three options provide, together with the International Partner labs, a payload volume that exceeds the Station Redesign Team requirements of 35 cubic meters. The Attached Pressurised Module and Japanese Experiment Module, satisfy with their 20 plus 10 International Standard Payload Rack's equals 34 cubic meters, this requirement to 97 percent, based on a net payload volume of 1.13 cubic meters per staged rack. The additional rack space provided by the United States ranges from nine racks (Option A), through 14 racks (Option B) to 40 racks (Option C) resulting in a maximum capability of 79 cubic meters, which is more than twice the volume required. Hence, the United States incurs unnecessary costs in providing this additional payload volume.

Simplification of the Designs

a. Columbus Attached Pressurised Module Interface Simplifications

Below is a listing of design simplifications proposed by one (or two) options. If proven to be technically acceptable, from a performance and risk point of view, it is recommended that these should be equally applied to all three options.

- Power interfaces via internal lines through common berthing mechanism, thus avoiding extravehicular activity during assembly. Proposed by Options A and C, should also be applied to Option B.
- Heat rejection interfaces via internal water lines through common berthing mechanism, in place of baseline external ammonia lines. Proposed by Options A and C, should also be applied to Option B.
- Deletion of oxygen resupply line and performing module repressurisation via bleed valve in the module hatch. Proposed by Option C, should also be applied to Options A and B.
- Portable sampling of atmosphere of attached modules via valve in hatch. Proposed by Option C, should also be applied to Options A and B.
- Simplified data management system with deleted workstation interoperability. Proposed by Options A and C, should also be applied to Option B.
- Simplified onboard software architecture by deletion of object based system. Proposed by Options A and C, also to be applied to Option B.
- Simplified International Standard Payload Rack data interface. Proposed by Option A, should also be applied to Option B (Option C has deleted International Standard Payload Rack interfaces).
- Deletion of distributed installed crew health and environment system equipment and use of portable units only. Proposed by Option C, should also be applied to Options A and B.

b. System Simplifications and Cost Reductions

Option C also has proposed other simplifications. If, after careful assessment, these are proven to be technically viable and produce the projected cost savings, they should also be applied to the other options:

- Deletion of the airlock.
- Bi-propellant refueling from orbiter orbital maneuvering system tanks with significant reduction in logistics needs. This will require a technology currently not available in the United States.
- Multiple use of proven Space Shuttle systems in lieu of new developments.

Simplification of Operational Scenarios and Concepts

The operations assessment team addressed many aspects of cost reduction. However, with respect to the ESA participation and ESA capabilities, the areas of possible cost savings to both NASA and ESA have not yet been considered in their full potential. These areas are identified below and should be jointly assessed in detail to confirm overall cost saving potential and further simplification of international interfaces, before baselining an updated operations concept for the Space Station. The areas identified are insensitive to the redesign option selected.

- Resource envelope allocation to total integrated (systems and payloads) element Attached Pressurised Module and relaxation of replanning cycle.

- Minimization of integrated functions and using distributed capabilities with fully delegated authority, i.e., management by exception.
- Performance of total ESA and non-ESA Attached Pressurised Module payload planning and integration activities by ESA at European facilities, based on the allocated Attached Pressurised Module resource envelopes.
- Execution of total Attached Pressurised Module payload operations control function from European Payload Operations Control Centre.
- Addition of Attached Pressurised Module systems operation control functions to the European Payload Operations Control Centre activities, with the exception of safety critical control function, which would still be executed centrally from the United States Space Station Control Center.
- Direct interfacing of the enhanced European Payload Operations Control Centre with only the Space Station Control Center for payload and system command and control functions.
- Consideration of use of a data relay satellite terminal on the Attached Pressurised Module for uplink and downlink data handling of all Attached Pressurised Module payload data, and distribution of non-ESA Attached Pressurised Module payload data from the European Payload Operations Control Centre to the distributed (NASA) user centers.
- Emphasis of crew training on skills rather than on procedures and consistent reduction of training program and training facility needs.

Option A Assessment

The overall accommodation and orientation of the Attached Pressurised Module is satisfactory. The interagency agreements of the joint program definition and requirements document and interface control documents are basically maintained with the only expected changes from the included interface simplifications.

To further simplify the Attached Pressurised Module interfaces, the NASA DC to DC converter units should be accommodated inside the core module on the core module water loop; thus, retaining design, development, verification and maintenance authority for this NASA equipment with NASA alone, thereby contributing to the required interagency management simplification and improving operational flexibility. The small impact to the number of International Standard Payload Racks in the core module is considered insignificant with respect to the simplification benefit and the abundance of total payload rack accommodation capability of this option.

The proposed simplification of the United States data management system by deletion of standard fiber distributed data interface, workstation interoperability, object based software architecture and replacement of standard Fiber Distributed Data Interface and the Institute of Electrical and Electronic Engineers standard 802.4 gateways by a simplified 1553B and 802.4 gateway approach, contributes to a significant overall Space Station simplification and to a reduction of complexity of the data management system interfaces to the Attached Pressurised Module. This also will have a positive effect on the ground system data architecture for the Space Station Control Center and other control facilities.

The power allocation to the Attached Pressurised Module is generally in line with the present baseline and useful operation of the international laboratories can be performed with the two photovoltaic and three photovoltaic module configurations.

Option B Assessment

The overall configuration is close to the Space Station Freedom baseline, with basically no changes to the agreed joint program definition and requirements document and interface control documents. The interfaces simplification identified for Option A should also be included in this configuration, therefore reducing programme complexity and related cost to both agencies.

In the data management system and onboard software architecture areas, the same simplifications as those defined in Option A should be included. There are no inherent configuration differences that would prohibit these additional changes.

Option C Assessment

This option provides within the United States module a payload accommodation of 40 racks that amounts to 30 percent over-fulfillment of the 35 cubic meter Station Redesign Team requirement for the total Space Station. The augmentation of this oversized capability by the addition of the Columbus Attached Pressurized Module (and Japanese Experiment Module) does not constitute a meaningful European program contribution. The role of the Attached Pressurized Module is changed from a mandatory provider of essential laboratory space to a user, accommodated on the Space Station; thus, diminishing with its housekeeping power needs, the already limited resources for payloads.

The interface simplifications as offered by Option C, and as addressed in the Payload Accommodations paragraph of this ESA assessment,contribute to a welcomed reduction of interface complexity. However, additional Option C specific interface deviations from the current baseline constitute significant technical impacts:

1. The current Attached Pressurized Module power system architecture, which is based on two main feeders supplied from two paralleled baseline DC to DC converter units, must be modified completely to directly interface with the four separate power feeders provided by this option. This will result in a significant loss of reconfiguration capability and will not allow high power payloads to be accommodated due to inability of source paralleling, which can only be overcome by synchronisable DC to DC converters. In addition, the deletion of the baseline DC to DC converter units will either require a change of all Attached Pressurized Module equipment to accommodate the increased voltage range, or the provision of central DC to DC converters. The initiation of a new DC to DC converter development programme will result in cost and schedule impacts to the Attached Pressurized Module program. Moreover, the power allocation to the Attached Pressurized Module systems and payloads must be increased by 8 to 10 percent to make up for the power losses in the DC to DC converters (and regulators) to attain baseline compatible power allocations.

2. The increase of the lower limit of the temperature range of the low temperature thermal control system water loop interface will result in significant impacts to the Attached Pressurized Module system, if the specified heat rejection capability is to be maintained. These impacts result from the need for a higher performance of the cold loop water pump (200W to 300W power penalty) with increased microgravity disturbance and a new design for the condensing heat exchanger (due to higher water inlet temperature). The latter change is a significant cost impact to the Attached Pressurized Module.

3. The location of the solar arrays does not allow continuous zenith or nadir viewing from the Attached Pressurized Module external viewing platform. The proposed modification to the solar array configuration, which provides a narrow viewing window between the arrays, only marginally improves the situation.

The proposed simplification of the fire detection and suppression system makes the required detection, localisation, isolation and first line of defense, i.e., removal of power and airflow impossible to achieve. The addition of zoning as per mandatory baseline requirement, the consequential separation of the power leads for detection, suppression and other equipment and distribution through different zones, as well as the potential introduction of dedicated air loops per floor, will significantly increase the mass of the vehicle, the power required for environmental control and life support system and the complexity of the data management system.

The quoted unregulated power values in this option must be decreased by eight percent to be comparable to regulated power values for Options A and B.

The total power available in the 28.8 degree inclination orbit flying local-vertical and local-horizontal is 31.4 kW. Even if the system power of 11 kW is considered credible in view of the huge air volume to be circulated in the large can volume, only roughly 20 kW are available for 40 payload racks without the Partner modules being attached and roughly 10 kW for 70 payload racks with the Partner modules attached.

Flying in solar inertial attitude increases the power by 12 kW. However, it is not certain that the Option C flight configuration can be kept in that attitude being stabilised by control moment gyros. Also, a not insignificant portion of the additional 12 kW are needed for torquing the control moment gyros in the solar inertial altitude.

The stated overall launch mass margin of less than five percent to cover design uncertainties and initial payload at this stage of the design definition are considered inadequate. This situation is compounded by the risk of a future mass increase due to the potential reintroduction of baseline fire detection and suppression features.

Overall Technical Risk Assessment

Option B is based on mature configuration, system, subsystem and equipment level designs taken directly from the current Space Station Freedom programme baseline, and derived from validated industrial design data. Therefore, ESA considers that Option B represents the lowest technical and programmatic risk.

Although Option A has introduced new configuration elements, with the exception of the use of Bus-1 in suboption A-1, these are to a large extent also derived from the existing Space Station Freedom programme baseline. On the other hand, Option A also has introduced design simplifications in many areas, which ESA considers somewhat offset the increased risk associated with the introduction of modified or new elements. Taking the above into consideration, ESA's overall assessment gives Option A a slightly higher technical and programmatic risk rating than Option B.

Option C is based on a totally new "system" concept, which essentially requires a new development programme start. Although Option C uses for approximately 37 percent of its system needs off-the-shelf equipment from the shuttle and Spacelab programmes, this can only contribute to cost savings at the equipment procurement level. Integration of this earlier generation equipment with a significant number (some 47 percent) of equipment level boxes from the Space Station Freedom programme baseline will present significant system engineering and equipment interfacing problems, as well as adding complexity to the overall integration and verification tasks. ESA considers that the relatively small cost benefits, which might be achieveable at equipment procurement level, can in no way offset the significant technical risks associated with system level integration and verification of this relatively immature configuration concept.

ESA cannot subscribe to the technical risk assessment contained in this report, which gives Option C an equal rating with Options A and B in the technical risk area.

Management Proposal

The overall management principles recommended in this report are seen by ESA as a very significant improvement over those currently implemented under the Space Station Freedom baseline programme. ESA supports the concept of retaining a combined Space Station programme management function and accountability, concentrated at one location. The proposed management principles should not only result in benefits for NASA, as described in the report, but also will significantly contribute to the streamlining, effectiveness and efficiency of the technical management interfaces to the International Partners.

Acquisition Strategy Assessment

The recommended strategy to select an industrial prime contractor to replace the current Space Station Freedom work package contractor system is fully supported by ESA. This approach will clearly separate the NASA "customer" technical and programmatic management responsibility from United States industry's programme implementation responsibility. It also will significantly contribute to the efficiency of the agency level technical interface management, and to agency level control of the necessary interfaces between the United States prime contractor and the European prime contractor in the area of technical data exchange and interface control documentation.

The NASA prime contractor role proposed under Option C is not supported by ESA. It would still retain the current complexity with respect to the International Partners by not distinguishing between customer and implementation contractor tasks.

Program Cost Assessment

A final option assessment can only be performed once detailed cost data is provided. These cost data will help ESA to evaluate its programmatic risks with respect to each of the options. Also the cost break-down into development, utilisation and operations costs with allocated reserves are essential aspects of the overall evaluation. Unfortunately, these data have not been provided to ESA at the time of this writing; thus, the ESA evaluation must still be considered incomplete.

Japan's Technical Assessment

Preamble

Japan's technical assessment by NASDA Station Redesign Team members is provided herein as a part of the Station Redesign Team report. Due to the immaturity of the guidelines or requirements that are applied to options assessment, NASDA members have assessed the options mainly based on the international "Operational Ground Rules" agreed to March 26, 1993, by the International Partners. The main activities of the redesign which internationals have been involved in since March 26, were the design guideline establishment, Space Station option selection and evaluation, and reduction of operations, utilization and transportation costs.

The sections titled "Japan's Contribution and Status" and "Evaluation Groundrules" are provided as the background of this evaluation. NASDA's technical evaluation consists of two parts. The first part contains general comments common to all options. The second part is dedicated to each option specifically addressing the impact and improvement of interfaces concerning the Japanese Experiment Module development, schedule, operations and utilization.

Japan's Contribution and Status

In response to the invitation by the United States President, Japan decided to participate in the International Space Station program by providing the Japanese Experiment Module, a permanently attached multipurpose laboratory, as a significant element. We believe the significance of our program is to:

- contribute to large-scale international science and technology research and development through developing, operating and utilizing the Japanese Experiment Module in the Space Station program;
- promote and enhance Japanese science and technology through microgravity experiments, Earth and astronomical observations, and fundamental space technology development testing;• establish fundamental space technologies required for future space activities including human space activities; and
- expand fields for industrial activities into space by promoting utilization of the space environment.

As described in the Intergovernmental Agreement, the Japanese Experiment Module, together with the United States core Space Station and other Partners' elements, will enhance the use of the Space Station for the benefit of all participating nations and humanity. The Japanese Experiment Module consists of the Japanese Experiment Module-Pressurized Module, the Japanese Experiment Module-Exposed Facility and the Japanese Experiment Module-Experiment Logistic Modules. The Japanese Experiment Module-Pressurized Module is a multipurpose research and development laboratory for conducting material science and life science in a microgravity environment; it accommodates 10 International Standard Payload Racks. The Japanese Experiment Module-Exposed Facility is a facility for conducting Earth and astronomical observations and experiments in a space environment characterized as microgravity, high vacuum, abundant solar energy and visibility of Earth, celestial bodies and the solar system. The Japanese Experiment Module-Exposed Facility accommodates 10 Japanese Experiment Module standard Exposed Facility payloads and has unique features of experiment support capability by the Japanese Experiment Module-Remote Manipulator System and accessibility from the Japanese Experiment Module-Pressurized Module via the airlock. About one half of the Pressurized Module and Exposed Facility user capability is open to the United States and Canada.

NASDA started the Japanese Experiment Module detailed design in 1992 after successfully completing the Japanese Experiment Module preliminary design review in July 1992. Simultaneously, advanced development tests for the components and systems, and Japanese

Experiment Module engineering model development, which is the first integrated Japanese Experiment Module system assembly, are being conducted. Most of the advanced development tests are scheduled to be completed by March 1994.

Japanese Experiment Module operations capability development and Japanese Experiment Module utilization preparation are also proceeding on schedule. Weightless environment test system construction began in March 1992 and will be followed by construction of other Japanese Experiment Module operation facilities, such as the Astronaut Training Facility and the Regional Operation Center for the Japanese Experiment Module. The system review of the Japanese Experiment Module operations system will be held in November 1993. The first announcement of opportunity for Japanese Experiment Module utilization was released in October 1992, and preliminary experiment selection is being conducted.

Evaluation Ground Rules

Evaluation in this report has been done from the following standpoints:

- Significance of Japan's participation
- Compliance with agreed "Operational Ground Rules"
- Impact on current Japanese Experiment Module design and development, and operations and utilization preparation
- Reduction of common operations cost.

General Assessment

Significance of the Japanese Experiment Module Program

Elements provided by Partners should have complementary roles in the International Space Station program so that each element contributes to the other in order to enhance the overall capability. Options A and B maintain Japan's role as a contributor. However, Option C changes Japan's role from contributor to unwelcome user by NASA's provision of an excessively large "big can" volume with relatively small resource capability.

Dual Access Requirement

There are several ways to realize this requirement. One is adoption of 51.6 degree inclination to enable Russian launch vehicle access. The impact assessment is shown in the next paragraph. Another option is to consider alternate access capability by Partners' launch vehicles, such as ESA Ariane, automated transfer vehicle and assured crew return vehicle, and Japanese H-II as depicted in the Intergovernmental Agreement and Memorandum of Understanding, while maintaining 28.8 degree inclination to avoid adverse impact on Space Shuttle launch capability. The United States Titan IV carrying the Soyuz assured crew return vehicle and/or the unmanned Progress further ensure multiple access capability for logistics supply and assured crew return vehicle replenishment. In this scenario, dual access for crew rescue could be achieved by using the Space Shuttle and assured crew return vehicle. This option would surely enhance International Partners' contribution and reduce United States development cost.

51.6 Degree Inclination Access

Current weight of the Japanese Experiment Module's first flight, excluding all payload outfitting, is about 2,800 pounds over the given Space Shuttle launch capability for a 28.8 degree orbit, as shown in Table 37. Therefore, the advanced solid rocket motor as baselined in the current Space Station Freedom program or the aluminum lithium tank for Japanese Experiment Module launch with some extent of payload is required without depleting NASA reserve. Space Shuttle launch capability of 25,000 pounds with present redesigned solid rocket motor for 51.6 degree orbit is unrealistic. Although addition of the aluminum lithium super light weight tank increases Space Shuttle launch capability by 7,500 pounds, there still exists a capability deficit of 5,300 pounds, requiring drastic Japanese Experiment Module downsizing. This will result in reducing International Standard Payload Rack accommodation, which is unacceptable to Japanese users. This makes the Japanese Experiment Module program almost worthless from the standpoint of return on investment. From both Japanese Experiment Module development and operations aspects, the aluminum

Table 37
Japanese Experiment Module first flight weight budget status

Japanese Experiment Module-Pressurized Module and Remote Manipulator System	32,905 lbs.	
NASA Deliverables	2,630 lbs.	
Payload, Spares	5,380 lbs.	
Subtotal		40,914 lbs.
Off-load	-8,057 lbs.	
Japanese Experiment Module Cargo Element		32,859 lbs.
Space Station Freedom Program Margin	1,800 lbs.	1,800 lbs.
Total of Japanese Experiment Module		34,658 lbs.
Orbiter Operator Weight	5,980 lbs.	5,980 lbs.
Total of Cargo Element		40,638 lbs.
Launch Performance (28.8 degrees)	37,800 lbs.	37,800 lbs.
BALANCE		- 2,800 lbs.

lithium super light weight tank and advanced solid rocket motor are musts for the program to employ 51.6 degree inclination orbit. Meanwhile, the advanced solid rocket motor is rescheduled to be available in late 2000, delayed more than one and half years from the Space Station Freedom baseline of March 1993. The resulting Japanese Experiment Module launch deferral is not acceptable due to its impact on the Japanese Experiment Module development and utilization schedule.

Space Shuttle is the baseline transportation for Space Station, and all Partners utilize the Space Shuttle for logistics and utilization flights. Once the Japanese Experiment Module is on-orbit, Japan will share the common operation costs including transportation, and pay transportation costs for its payloads and system spares for maintenance. With this in mind, reduced Space Shuttle launch capability for the 51.6 degree orbit will impose drastic operations cost increases on all Partners due to additional Space Shuttle flights.

Common Requirements and Interfaces

The requirements applied for each option should be identical for fair comparison. The essential Space Station Freedom requirements of the current program definition and requirements documents and joint program definition and requirements documents and interface control documents should be maintained. Relaxation of requirements for design simplification, which is acceptable to all concerned parties, should be equally applied to all three options. However, requirement changes that adversely impact on Partners shall not be applied.

Safety Requirements

Safety requirements, such as the Safe Haven and the fire detection and suppression system, should be maintained. NASDA has accepted the fire detection and suppression system with significant design change after lengthy negotiation because of the very strong enforcement of the NASA safety requirements.

Data Management System Simplification

The change of the data management system architecture and associated software for the interface simplification would be accepted as long as it is mutually beneficial. However, drastic simplification would impose on-orbit operational constraints that cannot be accepted by operation.

User Power Availability

In each option, two solar arrays with international modules does not provide sufficient user power, especially during the orbiter berthing. Early delivery of the third solar array is recommended.

Cost Comparison

The official cost data for evaluation is not available at this moment. However, for cost comparison among options, the cost sensitive requirements, such as the 30 kW user power, Space Station-based extravehicular activity capability and assured crew return vehicle should be the same.

Operations Concept and Cost

The operations assessment team reported the new operations concept and idea to contribute to reducing the Space Station operations cost. We generally welcome the report and hope that the implementation will be well performed. However, we have several concerns that may cause significant impact on the Japanese Experiment Module operations and its cost. Concerns identified so far are:

- Credibility of the new proposed operations concept
- Impacts on the common cost sharing
- Impacts on interface of the ground systems between NASA and NASDA
- Impacts on number of personnel to be sent from Japan to the integrated tactical operations organization, Space Station Control Center, and Payload Operations Integration Center
- Space Shuttle launch price (great influence on the Japanese Experiment Module operations cost as well as the common operations cost)

These items should be jointly assessed or clarified in detail among Partners before baselining the new operations concept.

For Option C, considerably reduced operations cost is reported, but we understand that this cost reduction is made mainly by the simplification of assembly operations and that matured operations cost is almost same as those of other options. Option C operations concept with reduced extravehicular activity will cause impact on Japanese Experiment Module maintenance.

Options Evaluation

Option A

This option is technically a derivative of Space Station Freedom with a reduced number of elements, deletion of alpha-joint, and use of the existing Bus-1 for the propulsion and control. The international commitment of joint program definition and requirements documents and interface control documents, and schedule are well maintained. The Japanese Experiment Module attach location looks acceptable for microgravity environment and the Exposed Facility payloads viewing. Deletion of the alpha-joint would limit the continuous observation missions for the Japanese Experiment Module-Exposed Facility payloads. Adding back the alpha-joint would enhance the power capacity and provide continuous viewing for the Exposed Facility payloads. The Japanese Experiment Module system power allocation of the Space Station Freedom baseline is maintained at 5.65 kW. The data management system interface with 1553B data bus should be coordinated and agreed upon to avoid imposing a big impact on Japanese Experiment Module data management system architecture and equipment design. The change of thermal control system interface from external to internal simplified the interface and reduced the extravehicular activity. The electrical power interface equipment of DC to DC converter units, which reside on the Japanese Experiment Module, should be moved to inside the United States core module to simplify the international interface. The use of existing and Space Station Freedom equipment makes the system viable and the cost estimate realistic.

Option B

This option is almost the current Space Station Freedom baseline. The option maintains the international top-level commitment with minimum changes on agreed joint program definition and requirements documents and interface control documents' technical requirements; this option has the least impact on the Japanese Experiment Module. Small interface changes in the field of the data management system will be necessary, but they are acceptable.

The adoption of appropriate system simplification will reduce the life-cycle cost and make this option viable.

Option C

This option provides a quite new Space Station design concept. The United States provision of large volume with very limited resources and user services will call into question the need for the additional volume of international modules. This means this option does not preserve the genuine partnership depicted in the Intergovernmental Agreement. We should remember that the Partners worked together more than three years to define a set of complementary program contributions before signing the Intergovernmental Agreement and Memorandum of Understanding.

The generic view for this option is that, because of the Space Shuttle modification and single launch nature, it imposes major potential programmatic and technical risks on the program. A single accident may collapse the program in a moment, and schedule delay and cost increase will more likely happen compared with other building block approach options. These features will impose risks on the Japanese Experiment Module development and less flexibility in the utilization planning.

Looked at from the point of Space Station occupied base to Japanese Experiment Module interface, it introduces simplified subsystem architectures, some of which do not comply with essential requirements in program definition and requirements documents and joint program definition and requirements document and interface control documents. The proposed interface imposes an adverse cost impact on Japanese Experiment Module subsystems, such as the electrical power system, data management system, and thermal control system in their redesign and additional development. Major impacts identified are:

a. The electrical power system interface with four power feeders shared with the Attached Pressurized Module severely restricts power channel usage in the Japanese Experiment Module and is very likely to force architectural redesign in the Japanese Experiment Module. Four parallel DC to DC converter units should be dedicated to the Japanese Experiment Module as current interface baseline.

b. Unstablized power supply to International Standard Payload Racks in the core module disables relocation of International Standard Payload Racks to and from the Japanese Experiment Module or Attached Pressurized Module.

c. The Japanese Experiment Module system power allocation of 5.65 kW, which is the current baseline, is not clearly budgeted. Drastic reduction of the system power would require Japanese Experiment Module redesign.

d. The drastic change of the data management system interface and command and control scheme with 1553B data bus would treat the Japanese Experiment Module like a payload.

e. The thermal control system interface change from external to internal is acceptable. However, the change of the agreed interface temperature would impact on the Japanese Experiment Module thermal control system.

f. The deletion of the power data grapple fixture on the Japanese Experiment Module may increase the risk of Japanese Experiment Module assembly, because there would be no contingency power supply capability for heating.

g. The physical clearance between the solar array and the Japanese Experiment Module Exposed Facility is quite small and may cause dynamic and thermal interference. The assembly using the Space Station Remote Manipulator System could be a critical task also.

h. Exposed Facility missions will be restricted because the solar array will limit the Exposed Facility field of view. In addition, when this Space Station flies solar inertia mode to increase electric power, Japanese Experiment Module-Exposed Facility payloads, which need continuous Earth or celestial observation, will be almost worthless.

Specific critical areas, which need to be reviewed for compliance with requirements and the system feasibility, are:

a. If the single large volume is punctured by debris penetration, for instance, the methods of the repressurization and necessary hardware and logistics transportation for survival, i.e., Safe Haven, are not clear. The puncture of the module could mean the end of the Space Station life.

b. Proposed deletion of the established fire detection and suppression strategy, especially fire localization by multiple cabin zones, looks risky from the point of safety. The partitioning of the volume, sensor locations, the fire suppressant location, and the by-product clean up process should be shown.

c. The verification process is not firm. For such a major project, the modified Space Shuttle test flight should be included as a part of the verification program to avoid catastrophic damage to the Partners, as well as the United States.

d. The power consumption of the environmental control and life support system is unreasonably low compared with the current Space Station Freedom environmental control and life support system despite having the larger volume and the same hardware as Space Station Freedom. Comparably low environmental control and life support system power consumption must increase if safety requirements of partitioning are adequately implemented.

e. The solar arrays, the body mounted radiators and the Canadian Arm are folded and attached to the large can during launch. However, during ascent, the can will be heated and deformed by the pressure change. The design should be verified.

f. Safe disposal of this large module is not clear.

From management viewpoint, the schedule risk is observed because it has to be restarted from the preliminary design with a new NASA management organization and revised contracts. Establishment of the new management structure and negotiation of the costs with the contractors are time consuming processes and may result in schedule delay.

Summary and Option Grading

In summary:

a. Option C has very limited continuation from the current program and sacrifices Partners' past effort by forcing drastic change of internationals' role and interfaces. In addition, it is premature in design and very risky in its nature. Therefore, this option cannot be accepted.

b. Option A and Option B are within acceptable range; these have several items to be resolved though.

c. As for the orbital inclination, it is strongly recommended to go with the current baseline of 28.8 degree considering the current Space Shuttle capability, advanced solid rocket motor development plan, and alternate access capability to the Space Station by Partners.

Canadian Space Agency Technical Assessment

Introduction

This report provides the Canadian Space Agency's (CSA) technical assessment and rating of the Station Redesign Team's Options A, B and C. The technical assessment is summarized in the table titled International Partners Option Parameters-MSS Accommodation. The tables titled International Rating Sheet-MSS Accommodation, provide our rating of each option against top-level criteria.

It is assumed that the commitment to build and operate a Permanently Manned Civil Space Station in accordance with the Intergovernment Agreement and the Memorandum of Understanding will be maintained, and these agreements form the point of departure for the assessment and ratings.

Due to the particular nature of the Canadian contribution and its role and integration in the station infrastructure, our assessment deals primarily with robotics assembly and external maintenance of the Space Station and impacts on the Canadian program.

For its contribution to the Space Station, Canada is developing a Mobile Servicing System, and its ground support infrastructure, to play a key role in the assembly and external maintenance of Space Station Freedom, and its user facilities.

The Mobile Servicing System includes a large manipulator (Space Station Remote Manipulator System) and a dexterous robot (Special Purpose Dexterous Manipulator). Both robots have been designed to operate from a base structure that includes special fixtures (payload and orbital replacement unit accommodations and a propulsion module attachment structure) to temporarily stow and provide services to Space Station components and payloads during Space Station assembly and maintenance operations.

The robots, the base structure and payloads are moved along the entire length of the Space Station on a United States supplied mobile transporter. The robots can also operate from special power data grapple fixtures located on the Space Station. On-orbit repair of the robots is performed on the Mobile Servicing System's base structure. A truss mounted maintenance depot is provided for spares stowage and potential accommodations for attached payload experiments.

The Mobile Servicing System baseline design operates as an integrated robotics system and as the focal point for concurrent robotics and extravehicular astronaut activities.

The Mobile Servicing System entered its manufacturing phase with the first of a series of critical design reviews taking place in December 1992, with the second scheduled for August 1993.

It is against this background that Canada participated in the United States initiated Space Station redesign activity, and we made this assessment.

Assessment of the Space Station Redesign Options

Approach

This report summarizes the result of technical and schedule assessments of the redesign options, carried out by the Canadian Space Agency with support from its prime contractor, SPAR Aerospace Limited. Our assessment has been made against the options design data that was formally frozen by the Space Station Redesign Team during the week beginning May 10.

This assessment is incomplete because of the preliminary nature of the options design data available for review, the lack of a coherent set of requirements against which all options could be measured, and the unavailability of detailed schedule, cost and risk data.

Our assessment of each option has been made relative to the Space Station Freedom baseline. In the tables we have quantified our assessment where possible. For technical and cost parameters that cannot be quantified, due to their complexity, an appropriate (*high, medium, low*) qualitative compliance-to-the-baseline assessment has been given. Specific cost impacts on the Mobile Servicing System are not provided, due to estimating time constraints and the immaturity of the Space Station designs and their schedules.

In the international rating charts we have rated each stage of each option as if it were the end-point of the program. This was done in accordance with the guidelines of the Station Redesign Team, but it results in a low rating for the early stages of Options A and B, which we would have given a higher rating if they were transition points to the permanently manned Space Station envisaged in the international agreements governing the program.

Summary Assessment

Canadian user requirements can be met by the three options once they achieve the Permanent Human Presence with International Capability. Each option maintains our robotics role, but to varying degrees of compliance with the baseline.

We believe that Option B has the best chance of success with the least amount of risk, because it is based on a mature and well understood design. Also, it maintains the complete role of the Mobile Servicing System as an integrated robotics system used for Space Station truss assembly and other assembly tasks, the transportation of massive components about the Space Station, and as a maintenance facility for robotics and crew at various worksites. Of the three designs, Option B has the least impact on the Canadian program. Option B also maintains the Space Station partnership in accordance with the agreements.

Option A, in its present configuration, has a much lower chance of success because the assembly will be very difficult and provisions for efficient maintenance no longer exist with the deletion of the Mobile Servicing System's transporter, base structure and maintenance depot. Furthermore, distributed system architectural and launch accommodation changes, as well as schedule slips, will have a significant impact on the Canadian program. In addition, we expect that as more detailed design information becomes available it will be apparent that the repackaging of truss mounted avionics has adversely affected robotics accessibility. An issue not connected to the Mobile Servicing System, but of concern to Canada, is the planned utilization of the Space Shuttle Remote Manipulator System beyond its current design specification. Option A is particularly vulnerable to this since there is no backup for truss indexing.

Though Option C has fewer launch and assembly operations, it is also less desirable than Option B since it adds a new dimension of program risk because of its immaturity and use of a new launch concept. The Space Station requires robotics support but, due to its configuration, it does not need an integrated and mobile robotics servicing facility. Canadian robotics have a diminished role on the Option C Space Station. As with Option A, there are substantial subsystem architectural changes that would require significant changes to Canada's contribution.

Common Issues

The Canadian program schedule is most affected in Option C with a 25 month delay, or longer if program go-ahead is not given by October 1993. Option B has the least schedule impact with a 15 month delay.

Our large robotics manipulator has been designed to be launched in the Space Shuttle mounted on a Space Station truss segment and the dexterous robot in the Mobile Servicing System's maintenance depot. Option C poses a radical change to the launch configuration for the manipulator. Options A and C, because they have deleted the maintenance depot, have affected the launch accommodation of the dexterous robot. These changes mean that new flight support equipment has to be developed.

In the baseline program the Mobile Servicing System end-to-end command and control system, including data management, video and robotics workstations, is an integral part of the Space Station architecture, with NASA and CSA contributing. Substantial changes to the avionics systems proposed in Options A and C would require an all new self-contained Mobile Servicing System command, control and video system.

The deletion of the robotics transporter in Options A and C impacts the Canadian program in several ways and represents a serious shortcoming in the Option A design. While it is possible for the large symmetrical manipulator to walk, like an inchworm, from one fixture to another, this complex operation was not intended to be its normal means of translation. Also without a transporter the dexterous robot can only be moved connected to the large manipulator, and this requires modifications to its design. A significant operations risk with this method of translation, particularly with Option A, occurs if there is a failure in the manipulator. It could then become stranded with no base structure where repairs could be carried out and no obvious way to carry it to a worksite or the orbiter.

The Operations Phase Assessment Team has recommended that minimum spares be kept on-orbit. This would change the availability of elements of the Space Station subject to failure. For the Canadian contribution, if it were not to have a robotics maintenance depot and base structure (as in the Option A and C designs) on-orbit maintenance of the robots would be difficult if not impossible. This changes the entire maintainability design of the robots, and impacts their operational availability.

The Canadian Space Agency, while recognizing the new dual access requirement, is concerned that the reduced shuttle upmass performance, which would result if the Space Station were placed in a 51.6 degree orbital inclination, may result in further schedule slips and launch cost increases.

The requirement for an airlock on Space Station is still to be resolved. If an airlock is not included in the design then an orbiter aft flight deck workstation or ground control must be provided for the Canadian robots.

Current Space Station Freedom program safety requirements demand that triple redundant power and data services be provided to the manipulator when it is operating in the cargo bay. It is not evident that this requirement is satisfied in the Option A and C designs.

The following paragraphs provide additional technical assessments that are specific to individual Space Station options.

Option A Specific

Option A would add significant new risk for assembly and maintenance of Space Station because of the deletion of the Mobile Servicing System transporter and base structure. In addition, the Mobile Servicing System development costs would be increased by the change to a self-contained robotics command, control and video system, and the proposed 21-month slip in the launch of the large manipulator.

The deletion of the transporter and the Mobile Servicing System base structure means that the Mobile Servicing System would no longer operate as an integrated robotics system or as the focal point for concurrent robotics and astronaut activities.

It is not evident whether the manipulator system operations required for Space Station assembly and maintenance would be feasible or whether the robots themselves could be serviced.

Without a transporter, robotics tasks will have to rely on the relocatable feature of the large manipulator. Instead of transporting payloads along the truss, the manipulator will have to move them from one special stowage fixture to another, while the combination of the manipulator and the dexterous robot relocate. This method of transporting payloads requires new fixtures on the truss, two grapple fixtures on each payload (only one is required in the baseline) and new procedures. The truss-mounted payload stowage fixtures are variants of similar fixtures designed for the Mobile Servicing System's base structure. However, these fixtures require power, a processor for control and monitoring and a video link for their cameras. These are not provided in the current Option A design. Translation using the relocatable feature of the manipulator also will double the time to complete a task, with the attendant demand on crew time. Finally, the designs of the robots have been optimized for the Space Station Freedom task times, an increase will therefore affect their reliability and maintenancé logistics upmass requirements.

The lack of robotics mobility will complicate the assembly of Option A and put a greater demand on the Space Shuttle Remote Manipulator System. In Option A, the Space Shuttle manipulator is used to index the partially assembled Space Station, i.e., to reposition the unpressurized berthing adapter. This represents a use of the shuttle manipulator in a task beyond its current design specification, thereby increasing the assembly risk, as no backup exists.

The deletion of the robotics maintenance depot and its use as a stowage location for robotics spares affects on-orbit robotics maintenance and also removes the possibility of using this structure for external payload experiments.

The proposed changes to the Space Station data management system will not allow the system to support the Mobile Servicing System's processing requirements. Also, the video part of communications and tracking system does not support robotics video requirements, nor do the lap-top computers that replace the multipurpose workstations. These design changes mean that the Mobile Servicing System will now require a self-contained end-to-end command, control and video system with workstations. The new Mobile Servicing System video system may have to include a special effects processor and other features to compensate for the combined effects of Option A's poor direct viewing of the Mobile Servicing System's operations, a reduction in the number of external cameras and lights, the deletion of the mobile transporter and a resulting greater reliance on robotics ground control.

The large Canadian manipulator is manifested on the second flight with its first operation required during the next assembly flight. To accomplish this task a special orbiter aft flight deck workstation will be required, since the alternative is to control the robot from the ground and this may prove to be too ambitious at such an early stage.

Option B Specific

Option B represents the least impact to Canada, though the schedule slips by 15 months, all elements of the Mobile Servicing System are retained, as are their interfaces, functionality and roles.

Changes in the data management and video subsystems could impact the Mobile Servicing System's indirect viewing, fault tolerance and the design of the MSS embedded software. Relevant changes include deletion of one external and two internal video switches, core standard data processors moved outside and simplification of the network operating system, the master object data base manager and the user support environment.

Option C Specific

Of the three redesign proposals, Option C represents the most radical departure from the baseline Space Station design. Option C diminishes the role, functionality and integrated operations nature of the Mobile Servicing System. It significantly changes the Mobile Servicing System design, schedule and cost.

The Option C schedule would delay the launch of the large manipulator by more than two years. Option C's subsystems are based on the Space Shuttle avionics architecture, which does not support the Canadian robots. As in Option A, the robots will require a self contained end-to-end command, control and video system, including all cameras and dedicated workstations. This is not provided in the basic Option C design.

Option C does not include a robotics transporter or base structure. However, unlike Option A, relocating the Space Station Remote Manipulator System by "inch-worming" from one fixture to another is more practical due to the Space Station configuration, if sufficient structural stiffness is provided for the fixtures. The absence of a base structure upon which to perform robotics repairs and a transporter to move a failed robot, is a serious deficiency.

The Option C proposal to use the robotics fixtures also for external payloads and experiments attachments is not practical without substantial changes to the subsystem architecture. Power, data and video to and from these fixtures are part of the, Option C-imposed, robotics self-contained command and control system, which does not support their use for payloads.

For Option C, the manipulator and the dexterous robot are essential for tasks, such as berthing the European and Japanese laboratory modules and the Italian logistics module, orbiter cargo unloading, repositioning the Soyuz spacecraft and dexterous tasks associated with maintenance and attachment of mechanisms. Option C has between 60 and 100 external robotically compatible orbital replacement units, but there is no significant on-orbit assembly, and the robotics maintenance tasks are reduced from that on the baseline Space Station.

The restricted access in the end-cone will likely result in the need to redesign the dexterous robot to allow it to work in more confined spaces.

The current Option C configuration has the large manipulator launched in the nose cone of the Space Station. Our initial analysis indicates that it may not be possible to launch the manipulator in this fashion. The baseline design supports the launch of the manipulator in the Space Shuttle on a section of the Space Station's truss.

The deletion of the robotics maintenance depot and its use as a stowage location for robotics spares affects on-orbit robotics maintenance and also removes the possibility of using this structure for external payload experiments. Also, the Mobile Servicing System's maintenance depot serves as the flight support equipment for the launch of the dexterous robot.

The plan to provide unregulated power to all users will require the addition of a conditioner for the robots or a redesign of their internal power supplies. The power losses associated with regulating the power could be up to 20 percent. The same applies for Canadian user experiments. This redesign could also increase the mass of the Canadian robots.

The keep-alive power allocated for the robots is significantly below that currently required and this remains an issue.

In summary, the power situation is viewed as a significant shortcoming of the Option C design, considering both the quantity available and its quality.

Conclusion

Based on the effects that the redesign options have on the design, cost, schedule and risk to the

Canadian program, the Canadian Space Agency prefers Option B.

Italian Space Agency Technical Assessment

Background

The ASI and NASA bilateral cooperation on the Space Station program is based on the ASI provision to NASA of two mini-pressurized logistics module's and possibly (to be jointly decided by end of 1994) of a minilab to house the 2.5 meter diameter centrifuge for life sciences research and its associated equipment.

In exchange for this provision, NASA will make available to ASI a percentage of its payload accommodation and user resources on board the Space Station itself, for use by ASI payloads, together with flight opportunities for ASI crew members.

For the operational phase, after the delivery, ASI will be also responsible for:

- Engineering support to operations
- Sustaining engineering
- Logistics

for the provided elements.

Mini-Pressurized Logistics Module Accommodation

General Assessment

As a general evaluation of the current options, it has to be remarked that Options A and B will substantially maintain the mini-pressurized logistics module role as it was envisaged when the NASA and ASI Memorandum of Understanding was signed.

However, the reduced Space Station life time from 30 years to 15 years maximum, will drastically reduce the negotiated compensation of the ASI investments for the mini-pressurized logistics module development that is based on the agreed percentage of Space Station pressurized volume and payloads accommodation utilization.

In Option C, even if the role of the mini-pressurized logistics module is increased, requiring an additional unit, ASI has identified an extremely high risk associated to the "single element" development and launch concept. That concept could cause the mini-pressurized logistics module role and associated ASI investment to vanish in case of failure or severe problems during programme development, launch and on-orbit life.

This risk is not present in the other options that are based on multiple element development, several launches and several pressurized volumes on-orbit.

ASI underlines that this potential high programme risk associated with Option C needs to be carefully evaluated, and the large investments that ASI has committed in order to support the Space Station to be reconsidered.

Logistic Scenario

All presented options identify the mini-pressurized logistics module as the only pressurized carrier for the logistic and utilization flights, after the first pressurized laboratory has been put in orbit.

A consolidated logistic scenario is not yet available for the three options and some top-level requirements, such as optimal sizing of the mini-pressurized logistics module for 51.6 degree orbit and accommodation of refrigerator or freezer racks, are still to be finalized.

The concept of dual access could imply use of elements of the Russian logistics infrastructure that may diminish the mini-pressurized logistics module role and/or imply use of expendable launchers such as Ariane V or Titan IV that would require adaptation of the mini-pressurized logistics module.

Impact on the Mini-Pressurized Logistics Module Design

Option A has identified the need for a stretched version of the mini-pressurized logistics module (to accommodate up to 12 racks) and the need for one additional unit in order to satisfy the logistic scenario.

Option A has identified the need for a modified version of the mini-pressurized logistics module to be utilized as a closet module.

ASI has performed preliminary studies to identify the feasibility to have a stretched mini-pressurized logistics module configuration and an efficient derivative for closet module application. ASI confirms the feasibility and the efficiency of the mini-pressurized logistics module configuration to be utilized for this application. A potential severe design change could be envisaged if the requirements that additional freezer or refrigerators will be implemented (four instead of the present baseline of two).

ASI confirms, as well, its willingness to provide the requested mini-pressurized logistics module units (three flight units) and the closet module upon the Memorandum of Understanding renegotiation.

For Option B, no impacts on the mini-pressurized logistics module design are identified to date.

For Option C, impacts are preliminary identified on electrical, data management and software; minor impact on mechanical and fluid systems.

At the present time, Option B and Option C have not identified a need for the mini-pressurized logistics module modified version. However, if the selected orbit for Space Station will be different from the present 28 degree orbit, it seems highly probable that a modified version will better satisfy the logistics scenario of both options, considering the different Space Shuttle lifting capability at different orbital inclinations.

ASI confirms its availability to provide NASA with the mini-pressurized logistics module configuration that optimizes the logistic scenario for each Space Station configuration, including the provision of the third mini-pressurized logistics module unit, as already stated for Option A

Schedule and Cost Impact

All options preliminarily show an increase of ASI incurred operations cost, due to a more extensive use of the mini-pressurized logistics module, with respect to the current Space Station Freedom scenario.

Option A (potential need for two additional units: the third mini-pressurized logistics module and closet module) and Option C (design changes and potential need for a third flight unit) imply an increase of ASI development costs.

All options envisage a delay of the first mini-pressurized logistics module flight, delay that ranges from 8 to 15 months with respect to the present baseline (September 1997).

Utilization Resources

They are defined in the Agreement as volume, power, crew time, Space Shuttle and Tracking and Data Relay Satellite System services.

As the operational scenario is not completely finalized, it is difficult to compare the resources made available to ASI by the various options. Nevertheless, two important factors must be underlined:

The 51.6 degree orbit greatly reduces Space Shuttle capabilities, resulting in a decrease of transportation services for the Partners.

The new lifetime of the Space Station (10 years against 30) greatly reduces the resources available over time.

Minilab Accommodation

Options A and B in their final configuration show the possibility to accommodate the Minilab.

Option C excludes this possibility because it proposes a "built-in" centrifuge.

Open Issues

Consolidated logistics scenario not yet finalized.

Optimization of the mini-pressurized logistics module size for 51.6 degree orbit to be assessed.

Requirements for accommodation of refrigerator and freezer racks to be finalized.

Potential adaptation of the mini-pressurized logistics module to expendable launchers to be defined.

Impact on the mini-pressurized logistics module of potential use of Russian logistic elements to be defined.

Presence of the centrifuge and relevant suitability of the Minilab to house it to be defined.

Cost

Introduction

The three alternative Space Station designs were costed with the direction of the Advisory Committee. Each of these was carried through Permanent Human Capability, including elements of the International Partners. In addition, several "stopping places" were costed, i.e., configurations which stop at the Power Station, Human Tended Capability or International Human Tended Capability. The incremental cost of selecting a different orbital inclination 51.6 degrees than the baseline 28.8 degrees was also calculated. There are many other factors which figure into the calculations, such as management and procurement approach, relationship to ongoing NASA programs, degree of civil service personnel involvement, schedule and cost risk assessments; these are addressed below.

The Redesign Team received explicit guidance from the NASA Administrator to ensure that each option had credible schedule and cost estimates, including specific schedule margins and appropriate reserves and allowance for program adjustment. For Options A and B, the results of the review of the baseline program by the NASA Administrator's Independent Cost Assessment Team were factored into the assessment. The independent assessment indicated that the baseline Space Station Freedom Program was behind schedule and faced a number of cost and schedule threats which would require additional funding to accommodate. This resulted in a decision to establish the Options A and B first element launch date at October 1997, a 19 month slip from the original baseline of March 1996.

A key factor in reviewing program options was to find ways to respond to total budgetary availability at three levels for the fiscal year 1994 through fiscal year 1998 period. These levels for the five year period amounted to $5 billion, $7 billion and $9 billion, respectively. The concomitant annual funding availability for fiscal year 1995 through 1998 was limited to approximately $1.0 billion, $1.2 billion and $1.8 billion per year, respectively, for the three levels. The September 1992 estimate of the equivalent funding levels for the Space Station Freedom Program covering the same five year period amounted to $14.4 billion, and required peak funding of $3.2 billion. This estimate preceded the disclosure of major schedule-related and additional funding problems required to complete the Space Station Freedom's development. It excluded the provision of an assured crew return vehicle, the costs of Space Shuttle transportation (other than unique support), and the salaries and benefits for the Space Station Program's civil service workforce.

Scope of Cost Estimates

The scope of the costs required for the redesigned Space Station options include not only the development and operations costs which are commonly represented as the Space Station program budget, but also the other directly coupled costs such as crew emergency return provisions, payloads and science, institutional support, Space Shuttle modifications and support, unique facility construction, and certain early flight research missions. This last item enables the science community to trade off building equipment which would be dedicated to the Space Station with precursor flights using the shuttle and Spacelab combination and to the Russian Mir space station. Finally, redirection of the program involves contractual changes for the Government's convenience which requires partial or whole termination of activities, and resultant outlays for a variety of costs, including employee severance pay, facility lease terminations and liquidation of outstanding purchase orders for parts and materials.

Baseline Program Approach

Currently, design and development of the United States elements of the Space Station Freedom Program involves over 16,000 employees of first and second-tier contractors, expenditures in excess of $2 billion per year, and over 2,300 civil servants. This workforce is geographically dispersed, especially so when the third-tier suppliers of parts and materials are taken into account. The civil servants are located in resident offices at the prime contractor's sites and at five principal NASA field centers and NASA Headquarters. Program expenditures cover all program cost elements of the prime contractor effort across what are referred to as "work packages." In addition, there are contractors developing facilities, equipment, and integrating software for crew training, flight and payload operations, engineering analyses and launch site processing. The latter is referred to as Operations and Utilization Capability Development. Coupled with these are the analytical engineering support and testing, program management and integration, and program control functions. These are referred to as supporting development and program engineering and integration The integration for the program as a whole, including the International Partners, is managed by the Space Station Freedom Program Office at Reston, Virginia.

There is also a significant integration requirement with the Space Shuttle, and the user community, the developers, sponsors and operators of scientific, commercial, and engineering payloads. The program requirement for compatibility with the launch and in-orbit capabilities of the Space Shuttle has been a key cost driver. Another key factor in the program costs has been the desires, if not requirements, of the customers for extremely low microgravity, long duration staytimes, rapid and easy access, high power levels and crew time. A third cost factor has been the provision of capabilities and services to the International Partners. In return, of course, the International Partners provide laboratory space and external payload and robotic capabilities.

Estimating Approach

Costs were estimated beginning in fiscal year 1994 and continuing through a 10 year mission life assumed to end (for estimating purposes) when the Permanent Human Capability milestone is accomplished or (if later) when the last International Partner module is launched. The budgetary phasing of the cost estimates has been analyzed under two basic assumptions. First, costs were phased assuming an unconstrained annual budget and targeted to deliver the earliest occurrence of program milestones (including a reasonable allowance for schedule margin). A second cost phasing was generated assuming a constrained program annual budget availability and program milestones were allowed to slip as governed by funding.

Basis of Cost Estimates

Development Program Estimates

In this activity, there has been a greatly diminished need for using cost estimating relationships derived from aerospace cost models. The relative design maturity of the systems and software for Option A and Option B has meant that the adjusted contractor design and development estimates for equipment at the subsystem and system level can be employed as a point of departure. The Government adjustments to the contractor cost have taken into account the current Space Station Freedom Program's technical issues, schedule problems and cost growth. As flight equipment deletions were identified on a subsystem by subsystem basis by the redesign process, the costs of the deleted equipment were deducted. Where systems simplifications were made, engineering estimates of the costs of the revised systems were made and included in the cost. In either case, add-back costs were included for analytical and physical reintegration and test of the subsystems affected. In addition, the Option A-1 configuration, which uses the existing Bus-1 spacecraft, assumes that NASA will modify two production spacecraft. Both the nonrecurring modification costs and the costs to replace the two Bus-1 flight articles have been included.

The cost estimating approach for Option C reflects the hybrid character of the design and development plans for this configuration. For those subsystems which use flight hardware derived from the Space Station Freedom Program, Option C uses the same approach of cost deletions and cost add-backs as was used in Option A and Option B. For those Option C subsystems which utilize Space Shuttle or Spacelab hardware, the approach is the same but uses the Space Shuttle program logistics procurement data as the pricing basis of flight system hardware components. For those Option C subsystems which are new designs (e.g., the structure of the large diameter pressurized module), parametric cost estimates have been used based on cost estimating relationships from NASA experience in human space flight. For the launch vehicle component of Option C, the cost estimates are based on data extensively reviewed in previous studies of Space Shuttle-derived heavy lift launch vehicles.

Since the ongoing Space Shuttle program provides equipment, systems, software, engineering and integration capabilities of use to Option C, an additive funding requirement approach was utilized to cost this option. That is, instead of allocating costs to the two programs on a prorated basis, the planned funding requirement to carry out the basic Space shuttle program of flights was retained as a Space Shuttle-identifiable budget requirement, and only the additive costs to this base to execute Option C were identified against Option C. This approach enables the true costs of continuing to fly the Space Shuttle to be separately identified from this design option for the Space Station. It also enables comparisons to be made of the unique funding requirements among the options.

Procurement and Management

A key element in the cost estimates for each option is the recognition that there is a substantial, realizable savings potential from management, organizational and contract changes. A major emphasis in the cost analyses is the quantification of savings which could result from the proposed changes to the existing program management approach. Major changes in program structure, degree of Government oversight, utilization of NASA civil service personnel and operational philosophy have the potential of enabling savings from the current Space Station Freedom baseline management cost. In some areas, the solution is to eliminate excessive management layers and thereby reduce personnel costs. A key to this is altering the present procurement strategy and adopting a single prime contractor who has overall integration responsibility. A corollary is reducing the size of the NASA program and project management staff and eliminating the standalone Level II (program level) at the Reston site. In addition, NASA personnel will be reassigned to perform specific operational functions where their expertise can be brought to bear most effectively. The operational philosophy will be altered to emphasize more autonomous operations and safe-hold failure responses, thereby reducing the size of control center staffs and supporting engineering personnel.

Several studies were done by the program management and program control subteams to assess the cost savings potential of proposed management changes. These included examinations of intelligence agency space programs which have delivered systems for 15 percent to 30 percent less when using a dedicated program office, analyses of historical NASA human program management analogs which indicate a 20 percent savings compared to the current Space Station Program, estimates of revised contractor and civil service personnel loading requirements due to consolidation and elimination of overlaps within the primes, and assessments from the Space Station Freedom Program Level II and Level III offices of potential reductions due to structural improvements, change management and other efficiencies. All of these analyses argue for taking cost savings into account when estimating future program costs. The issue has been the amount of cost savings realizable. Compared to the program plan in the fall of 1992, the estimates for Option A and Option B reflect an approximate annual savings of $300 million which is approximately 15 percent.

Operations and User Support

The elements of cost for Operations and Operations and Utilization Capability Development were discretely estimated by experienced NASA personnel engaged in the Operations Phase Assessment Team activities. The Operations costs cover not only conventional mission preparations, training, mission control, logistics, sustaining engineering, and management and integration, but also payload operations support, integrated payload training and payload analytical and physical integration into flight racks or other carriers. These two aspects were segregated during the team's analysis of costs.

In the search for the optimum tradeoff between cost and capability, the operations phase assessment team determined that the personnel, logistics, facilities and equipment costs could be reduced from present Space Station Freedom estimates either by accepting more risk or by combining facilities. Accordingly, in the final phase of the study, a significant cost advantage was determined to be present if the mission control and integrated training activities were not geographically distributed, as is the case with the current program's approach. The cost reduction over the fiscal year 1994 to 1998 period for this consolidation was estimated to be nearly $0.5 billion.

The estimates for user support estimates were increased over prior estimates because the team discovered inadequacies in the provision of certain common equipment and capabilities. Our estimate of the funding needed for additional laboratory support and related equipment was accordingly increased by over $130 million.

The basis for the operations cost reductions has been discussed in detail in the Operations section of this report. For costing, recommended changes in operations philosophy were incorporated, including combining mission control payload and housekeeping system operations and altering the approach to calculating the probability of sufficiency for meeting spares requirements. However, a 25 percent reserve was added to the estimates. This reserve level is somewhat higher than the normal 20 percent factor at this stage, but was selected in recognition of the potential for some alterations in the estimates, whether due to maturation or changes in operations approaches.

There are a set of cost elements within operations which form the basis for the reimbursement to the United States from our International Partners. These cost elements for operations have not been examined in depth or validated, although a preliminary estimate of approximately $500-525 million per year, exclusive of Space Shuttle launch costs, in constant 1993 dollars was generated for Options A and B. Time did not permit development of a similar costs elements estimate for Option C. In addition, the International Partners have requested an official NASA position on the pricing which would be employed for the Space Shuttle to conduct the launches of the Japanese and European modules and for operational support. We were unable to provide that information to the International Partners. It should be noted that, in the absence of the pricing policy determination, the cost estimates for the program do not reflect any offsets to the United States costs for any such potential reimbursements.

Space Shuttle Integration and Transportation Capability

This element of cost covers the requirements associated with integrating the Space Station into the Space Shuttle. The requirements range from the provision of docking hardware to orbiter payload bay keel fittings and extravehicular mobility units (commonly referred to as space suits). For options involving consideration of 51.6 degree inclination orbits, the aluminum lithium external tank was included in the cost estimates at approximately $300 million through fiscal year 1998, with a flight readiness in 48 months after authority to proceed. Assuming an October 1993 authority to proceed date, this schedule supports the Options A and B assembly schedule start dates of October 1997. All options had to include provisions for altering the Space Shuttle orbiter's reaction control system at a cost of approximately $70 million for Option B and $175 million for Options A and C.

Assured Crew Return Vehicle

The cost estimates incorporated for the Soyuz assured crew return vehicle assume the vehicle is modified to extend its orbital life beyond the current Russian baseline of approximately six months. NASA parametric cost models were used to generate the estimates of these modifications. In addition, the integration of the Soyuz into the Space Shuttle, including launch site processing, were costed. The estimates do not reflect input from the Russian Space Agency as to the cost of the Soyuz spacecraft or the modifications they would make to extend the orbital staytime. This is an area of greater uncertainty in the estimates than most areas.

From a life cycle cost standpoint, the estimates assume that in the early 2000s, the European Space Agency's assured crew return vehicle is developed and used by the Space Station program as the long-term solution. No United States costs were included in the estimates for this based on the general agreement within the Station Redesign Team after consultation with the European Space Agency representatives to the Team that a bartering arrangement would be a suitable costing assumption. To the extent that the member governments of the European Space Agency have not committed to a hardware development for the assured crew return vehicle, this represents a longer term cost risk to these estimates.

The costs representing the Space Station Freedom baseline program do include an estimate for a United States provided assured crew return vehicle. The estimate for this vehicle is approximately $1.2 billion for fiscal year 1994 to 1998, and an additional $0.5 billion to reach Permanent Human Capability. For comparative purposes, the Soyuz assured crew return vehicle cost could be assumed at values of $0.3 billion and an additional $0.2 billion, respectively.

Science, Technology, Applications and Engineering Research

The funding requirements for science, technology, applications and engineering research take into account not only the development of payloads to fly on the Space Station but also the support needed for the ongoing Spacelab program and cooperative international research efforts. The cost estimates for each option reflect the Station Redesign Team's strategy for utilizing the Spacelab, Russian Mir space station, and the Space Station. Given the differing flight sequences for the options, and the availability and quality of the research opportunities, each option reflects somewhat differing estimates for the annual budgetary resource requirements; these differences extend to the distribution among the various disciplines which would be funded from the approximately $1.5 billion of planned fiscal year 1994 to 1998 availability.

Prior to the development of the $1.5 billion figure, the Station Redesign Team's science, technology, applications and engineering research representatives developed an "unconstrained" estimate of budgetary requirements. This estimate exceeded $3 billion. Given the overall budgetary constraints for the Space Station redesign effort, the $3 billion option was considered not realistic. One assumption made in the development of the $1.5 billion value was that engineering research payloads from non-commercial entities would not compete for funds with life sciences and microgravity science and applications payloads. This is consistent with the absence of identified payload funding for engineering research in the NASA fall 1992 budget submission to the Office of Management and Budget. Due to that exclusion, the Office of Management and Budget did not decrement the fiscal year 1994 budget for Space Research and Technology as it did the budgets for Life and Microgravity Sciences and Commercial Programs. This does not preclude the flight of engineering research payloads on the Space Station. However, the Space Station would be considered another target of opportunity for flight experimentation, just as is the case with the Space Shuttle, Spacelab, and the commercial Spacehab carriers.

The Station Redesign Team and supporting personnel from NASA Headquarters and field installations developed and analyzed the cost estimates for experiment development for Spacelab research flights as well as payloads developed uniquely for the Space Station. These estimates were reviewed as to their basis, methodology, approach to using NASA in-house assets and maturity. Reserves were estimated for each major development. In addition, appropriate funding allowances were made for supporting lab equipment where that was necessary. The estimates reflect widely varying levels of maturity, ranging from modifications to existing hardware to developments of major new facilities.

A significant uncertainty in the estimates was the level of capabilities which would be furnished by key Space Station systems, such as the data management system and the communications and tracking system. In addition, the number and frequency of Spacelab flight opportunities is related to the assembly manifest planning for each option. For purposes of determining a resource value for the options, the approximate $1.5 billion was determined to represent an adequate basis for budgetary planning. Further analysis will be required once an option for the Space Station is selected.

Summary Results

Summary level results of the station redesign cost estimating analysis for each option and by

Table 38
Funding for Power Station configuration (1994-1998)

Billions of Dollars	Power Station Configuration				
	Option A-1	Option A-2	Option B		
Space Station Program	4.5	3.8	4.5		
Shuttle Integration	0.4	0.4	0.3		
Payloads & Early Flight Research	1.5	1.5	1.5		
Total, FY 1994-1998	6.4	5.7	6.3		
(Date Achieved)	Dec-97	Dec-97	Nov-97		
	FY 1994	FY1995	FY 1996	FY 1997	FY 1998
Modular Bus-1 (A-1)	1.4	1.6	1.5	1.1	0.9
Modular SSF-derived (A-2)	1.2	1.3	1.3	1.1	0.8
Improved Freedom (B)	1.3	1.4	1.5	1.2	0.9

phase are reported here. The total of the funding required for each option for the fiscal year 1994 through fiscal year 1998 period and to the end of the major phase are shown in Tables 38 through 41. There are two factors which are of importance in evaluating the estimates: one is the amount for payloads and early flight research, held constant at approximately $1.5 billion; the other is that the estimates do not reflect funding constraints. If funding constraints were imposed, the scheduled completion dates would obviously move out in time and the estimated costs at completion of the phase would increase.

As can be seen, none of the three Space Station redesign configurations for the Permanent Human Capability phase fall within the budget targets of $5 billion, $7 billion and $9 billion for fiscal year 1994 through fiscal year 1998, cumulatively. In reduced capability configurations for Options A and B, the Power Station configuration does meet the $5 to 7 billion target. (The cost totals for this configuration, as shown in Table 38, do not reflect the cumulative cost at the completion milestone; rather, the totals include the residual funding requirement for the remainder of fiscal year 1998. If put on a cost-at-completion basis, the totals would be reduced by approximately $600 million.) Extending the development of Options A and B beyond the Power Station phase to the Human Tended phase requires funding of approximately $11-12 billion during fiscal year 1994 to 1998. The Option A approaches would achieve the completion milestone prior to the end of fiscal year 1998. Option A and B's next plateau, the International Human Tended Capability phase, have estimated costs of about $12 billion for fiscal year 1994-1998, but require $2 billion and $4 billion of additional funding beyond that point for the two Option A approaches and Option B, respectively. Option C's estimated Permanent Human Capability fiscal year 1994 to 1998 cost of about $12 billion exceeds the $9 billion target level, and requires another $3 billion to completion.

These tables also show the annual funding requirements between fiscal year 1994 and fiscal year 1998 for each option. No option meets the

Table 39
Funding comparison through Human Tended Configuration

Billions of Dollars

	Modular-Bus 1 Approach	Modular SSF-Derived	Improved Freedom
FY 1994-1998 Funding			
Space Station Program	9.2	8.7	9.3
Shuttle Integration	0.7	0.7	0.6
Payloads & Early Flight Research	1.5	1.5	1.5
Crew Rescue Vehicle	N/A	N/A	N/A
Total	11.4	10.9	11.4
Post-FY 1998 Funding			
Program through Human Tended Capabil			0.3
Payloads and Other through Human Tended Capability			0.1
Total through Human Tended Capability	11.4	10.9	11.8
(Date Achieved)	Jul-98	Jul-98	Dec-98

	FY 1994	FY 1995	FY 1996	FY1997	FY 1998
Modular Bus-1 (A-1)	2.1	2.7	2.5	2.2	1.9
Modular SSF-derived (A-2)	2.0	2.4	2.3	2.2	2.0
Improved Freedom (B)	2.2	2.5	2.4	2.3	2.0

Table 40
Funding through International Human Tended Capability configuration

Billions of Dollars

	Option A-1	Option A-2	Option B
Space Station Program	9.5	9.0	10.3
Space Shuttle Integration	0.7	0.7	0.6
Facilities	0.0	0.0	0.0
Payloads and Early Flight Research	1.5	1.5	1.5
Total, FY 1994-1998	11.8	11.3	12.4
Additional Funding to Completion	2.14	2.16	4.03
Total at International Human Tended	13.89	13.42	16.40
	Jan-00	Jan-00	Mar-01

	FY 1994	FY 1995	FY 1996	FY 1997	FY 1998
Modular Bus-1 (A-1)	2.2	2.7	2.6	2.3	2.0
Modular SSF-derived (A-2)	2.1	2.4	2.5	2.3	2.0
Improved Freedom (B)	2.3	2.6	2.8	2.6	2.2

Table 41
Funding comparison through Permanent Human Presence

	Baseline Assessed	Modular-Bus 1 Approach	Modular SSF-Derived	Improved Freedom	Single Launch Core Station
FY 1994-1998 Funding					
Space Station Program	14.5	10.7	10.2	11.0	9.4
Shuttle Integration	0.4	0.7	0.7	0.6	0.6
Payloads & Early Flight Research	1.4	1.5	1.5	1.5	1.5
Crew Rescue Vehicle	1.2	0.3	0.3	0.2	0.4
Total FY 1994-1998	17.6	13.3	12.8	13.3	11.9
Post FY 1998 Funding					
Program through PHC	6.0	2.7	2.8	4.6	2.4
Payloads and Other through PHC	1.4	1.0	1.0	1.4	0.9
Total through PHC	25.1	17.0	16.5	19.3	15.2
(Date Achieved)	Mar. 2001	Oct. 2000	Oct. 2000	Decem. 2001	Jan. 2001

Annual Funding	FY 1994	FY 1995	FY 1996	FY 1997	FY 1998
Independent Assessment	3.0	3.3	3.7	3.8	3.7
Modular-Bus-1 (A-1)	2.4	3.1	2.9	2.5	2.4
Modular-SSF Derived (A-2)	2.3	2.8	2.8	2.6	2.4
Improved Freedom (B)	2.3	2.6	2.9	2.8	2.7
Single Launch Core (C)	1.8	1.8	2.8	3.0	2.4

PHC-Permanent Human Capability

annual funding targets of $1.0 billion, $1.2 billion or $1.8 billion at full Permanent Human Capability while simultaneously achieving the schedule milestones desired. To have achieved the schedule milestone for this capability for either Options A or B would have required a radical alteration of their assembly plans, which generally are consistent with those of the Space Station Freedom Program, and a concurrent redefinition of the Permanent Human Capability milestone to exclude the on-orbit installation of the International Partner's modules. This milestone definition is of particular importance in calculating the costs through Permanent Human Capability of Option C, because the referenced completion date of January 2001 is over a year later than the planned permanent habitation of its core station.

Despite the fact that no option meets the cost targets except for the Power Station plateau point, the redesign options do offer potential savings when compared to the existing baseline Space Station Freedom Program projected costs. This comparison is indicated in Table 41, but is perhaps better illustrated in Figures 109 through 112, which provide a graphic representation of the Permanent Human Capability costs. The first figure provides the comparative funding for the fiscal year 1994 to 1998 period, the second from fiscal year 1994 to the completion of the phase, the third displays the ten years of operations costs, and the final aggregates costs for the entire period. The estimates exclude the approximately $10.3 billion expended through fiscal year 1993 for costs for the program, facilities, integration and payloads. The estimates on Figure 110 presenting the fiscal year 1994 to completion of Permanent Human Capability costs, should be understood as reflecting not only the real differences in the content of each option, and its

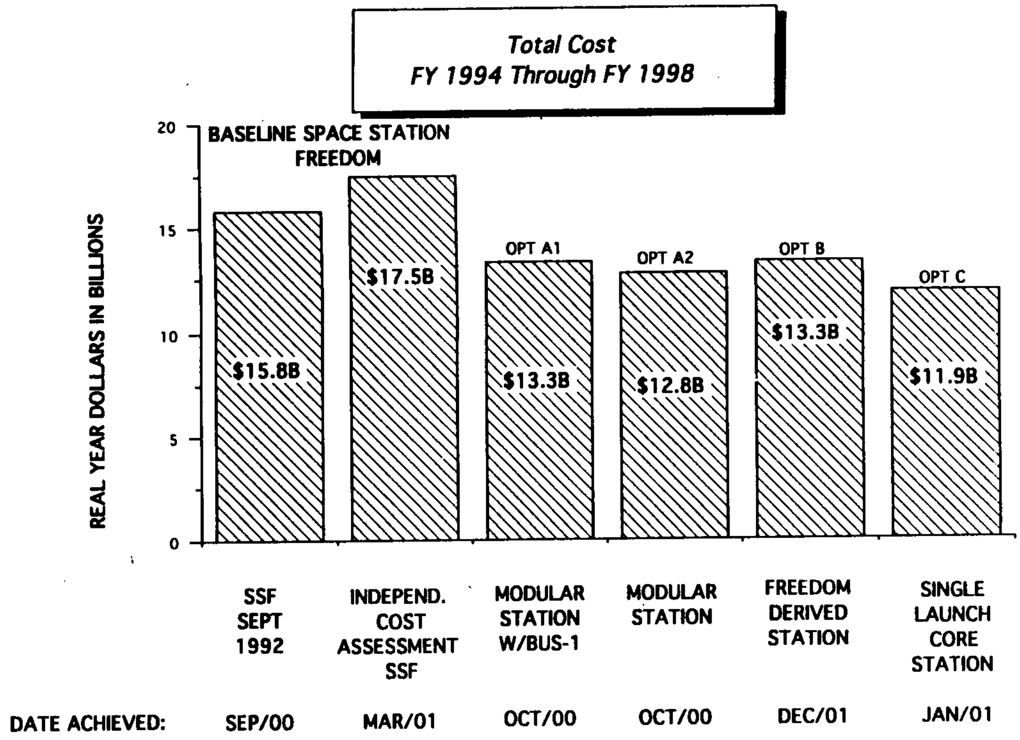

Figure 109
Comparative funding - fiscal year 1994 to 1998

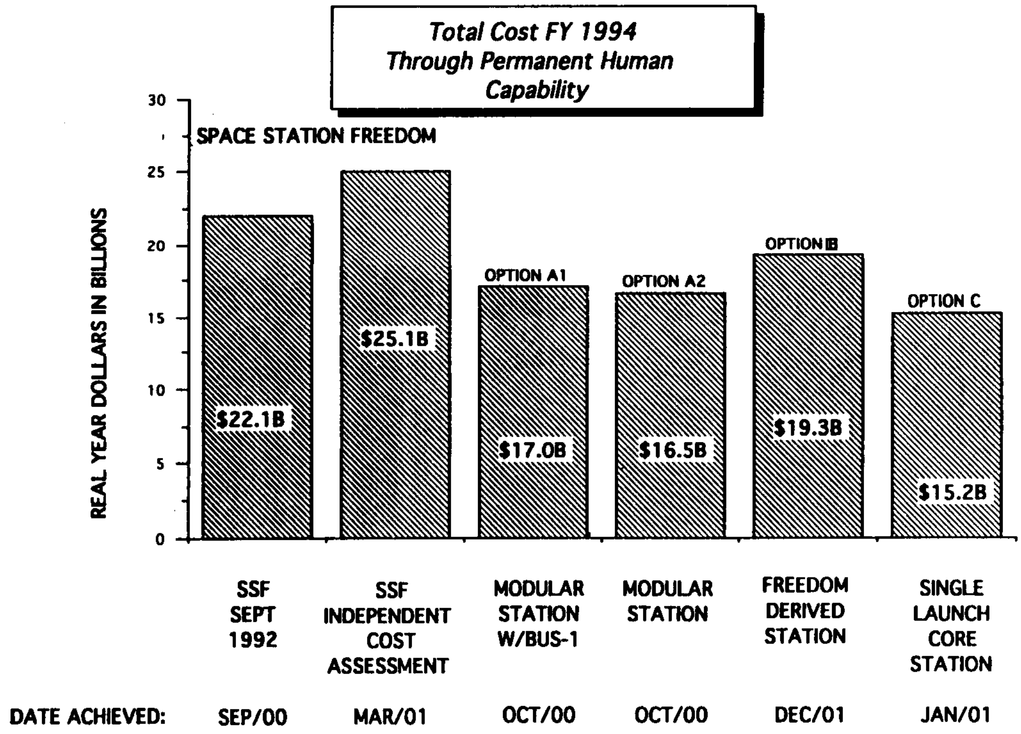

Figure 110
Comparative funding from fiscal year 1994 to completion of Permanent Human Capability

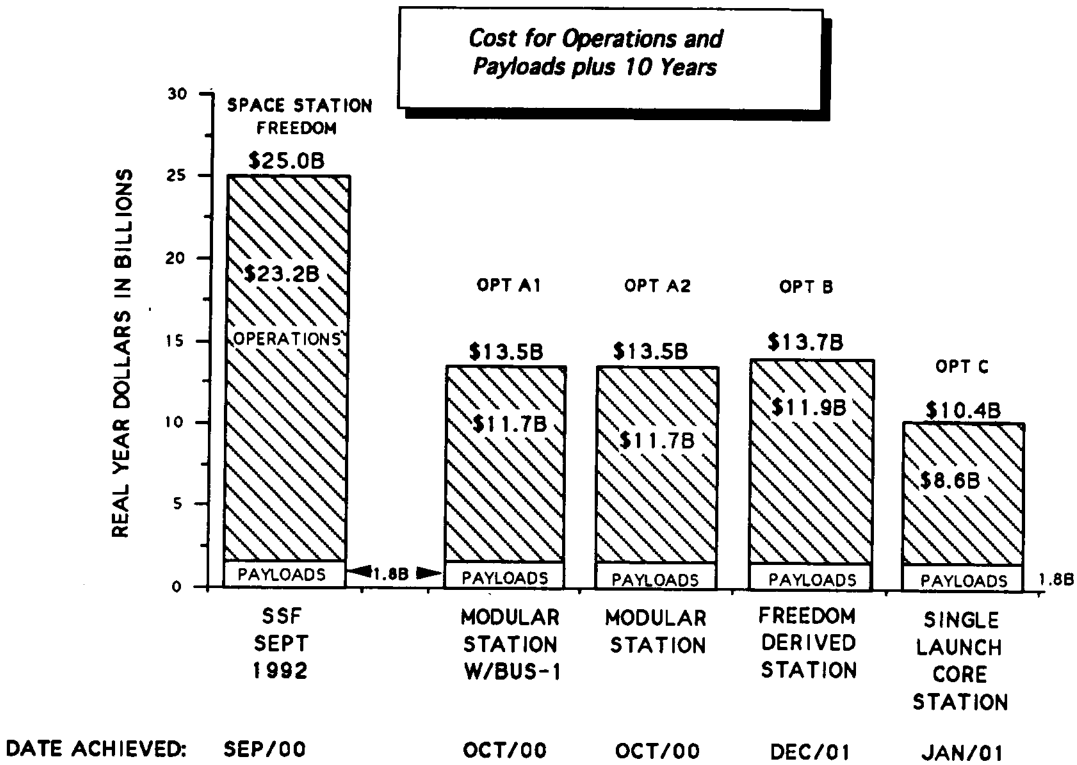

Figure 111
Ten years of operations costs

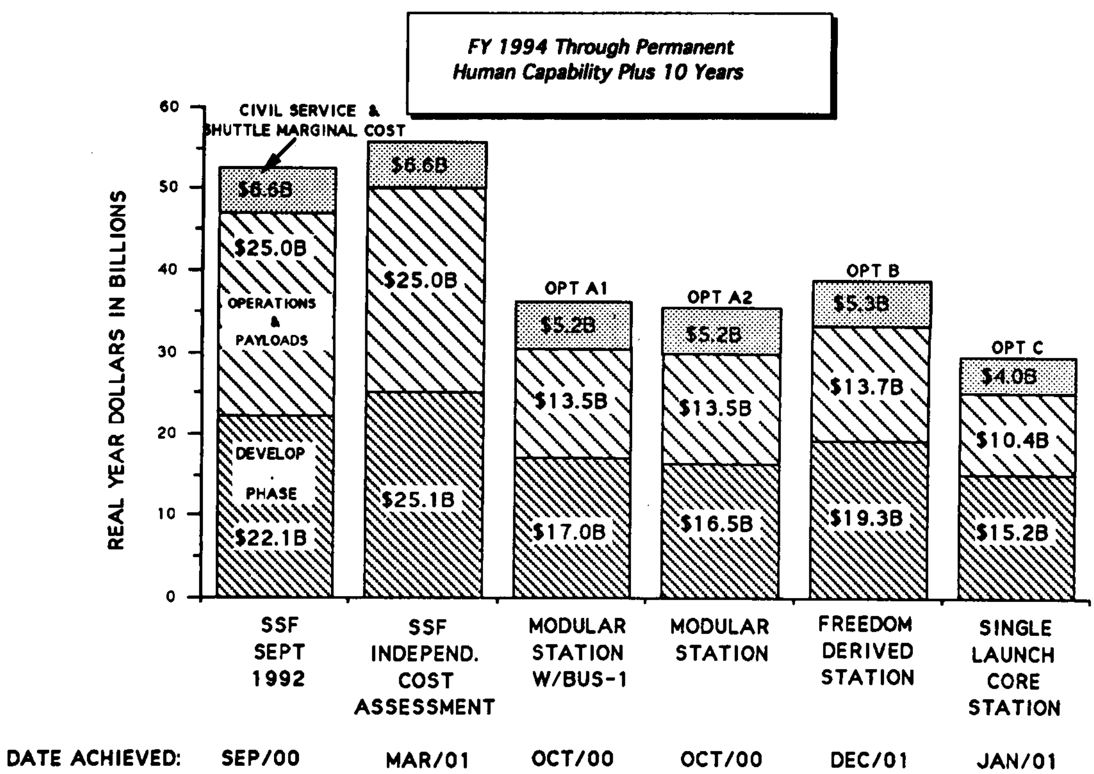

Figure 112
Aggregate costs - fiscal year 1994 through Permanent Human Capability plus 10 years

according cost, but also a time dependency relationship. In aggregating the costs through the month and year of the completion date, the team realized that the comparison could reflect adversely on Option B's decision to defer the assembly completion date in favor of continuing the baseline Space Station Freedom's flight plan of three utilization flights per year. Optimization of the hardware build and cost phasing plan could enable an earlier completion date and avoidance of the ongoing operations cost which accrue to the later date.

Risk Analysis

Any cost estimate for a program as complex and as challenging as the Space Station obviously has significant uncertainties or risk associated with its development and operating cost estimates. These risks are due to uncertainties that are a fact of life for space system developments, particularly those that involve the added difficulty of assuring the safety of human beings in the unforgiving environment of space. In addition, there are estimating uncertainties associated with the management streamlining, the hardware deletions and simplifications, risks in the "to-go" cost of the Space Station Freedom Program which formed the basis for the estimates for the redesigned station options, possible growth in cost driving variables and content and other design uncertainties that lead to estimating inaccuracies.

Even more pertinent, the cost estimates of these Space Station redesign options are inherently complicated by the fact that the three options reflect different levels of understanding and design maturity. The levels of reserve have been calculated on each subsystem, based on an evaluation of the design and development maturity level. The evaluations of these maturity levels were provided by the technical community to the cost estimating team. The reserves discretely applied ranged from 35 percent for new design work to 25 percent for a preliminary design review level of definition, and for higher levels of definition, 20 percent for the critical design review level, 15 percent for modification to existing hardware and 10 percent for "off-the-shelf" hardware.

In an attempt to evaluate the possible range of error in our estimates, given the differing levels of understanding and design maturity among the options, a cost risk analysis was also performed to illuminate the possible effects of this cost uncertainty on the results. This was accomplished by establishing confidence intervals around the discrete subsystem level estimates of each of the major cost elements of each option. These ranges were based on risk and reserve assessments and were expressed as low, most likely and high values. A Monte Carlo analyses was then performed which aggregated simulated subsystem level costs up to total program costs over several hundred simulation passes. The analysis was performed for the baseline Space Station Freedom Program, Option B, Option A-2 and Option C. Option A-1 was not evaluated due to time constraints, but should be understood as falling within the Option A-2 and B range, with considerably less cost risk associated with the basic Bus-1 spacecraft systems, and equivalent risk for the design modifications required to the Bus-1.

The results of the cost risk analyses show that the current (as of April 1993, not September 1992) estimate for the Space Station Freedom Program has a 45 to 50 percent confident cost estimate without reserves. The addition of reserves improves the confidence of the estimates to 65 to 70 percent. For Option B, the confidence of the basic estimate without reserves is also 45 to 50 percent. The addition of reserves brings the confidence of Option B up to 65 to 70 percent and the use of the allowance for program adjustment for in-scope changes brings the overall confidence of the Option B cost up to 70 to 75 percent. Option A's confidence level without reserves is somewhat lower at 40 to 45 percent; this reflects the somewhat wider cost ranges that were input to the analysis for this option to account for the uncertainties associated with the system and management changes being implemented into the program. The addition of reserves increases the confidence of Option A to 65 to 70 percent and the addition of allowance for program adjustment brings the overall confidence up to 75 to 80 percent. Finally, Option C has a 30 to 35 percent confidence attached to its cost estimate without reserves which reflects the relatively higher risks associated with the increased levels of new design and integration associated with this option. The addition of reserves improves Option C's confidence to 65 to 70 percent and the addition of allowance for program adjustment

Table 42
Space Station Freedom September 1992 NASA estimates compared to Redesign Options

	FY 1994-1998			
Program Estimates	12.4	+ 2.0	=	14.4
Additions:				
Shuttle Integration	0.4			
Facilities	0.2			
Payload Development	1.4			
Soyuz/U.S. ACRV	0.3/1.2			
Research Operations Support/ SBIR Increase	0.2			
Starting Point 5/7/9 Billion	14.9/15.8			
Realism:				
NASA SSF Independent Cost Assessment	1.8			
Realistic Starting Point	16.7/17.6			

Program Estimates 14.4 Compares To:

Option A-1	10.7
Option A-2	10.2
Option B	11.0
Option C	9.4

Realistic Starting Point 16.7/17.6 Compares To:

Option A-1	13.3
Option A-2	12.8
Option B	13.3
Option C	11.9

increases the overall confidence to about 75 to 80 percent.

These analyses do not consider the effects of funding constraints which are currently being experienced by the Space Station Freedom program nor those which could be applied to the selected option. The risk analysis only provides an assurance that the base estimates and the level of contingencies included do not inherently understate the current program costs, if the evaluators of the design, development and operations risk have accurately appraised the risk. Past experience with space systems developments indicate that this caveat should be appropriately highlighted. Nonetheless, the results of the risk analysis provide moderate assurance that the program is doable for the resources estimated.

Observations and Conclusions

The results of the Station Redesign Team's work need to be understood in the context of the estimates for the Space Station Freedom as it was configured last fall. The Space Station Freedom Independent Cost Analysis Team found that the estimates provided to the Office of Management and Budget by NASA in September 1992 significantly understated the program costs and schedule difficulties. A separate report has been prepared by that team. For comparative purposes, Table 42 illustrates the magnitude of the reductions in the program cost estimates achieved in the redesign process.

The Station Redesign Team has offered a set of design, management, operation and payload options for consideration and evaluation by the Advisory Committee on the Redesign of the Space Station, the Administration and the Congress. Major reductions were achieved in the projected costs of operating the Space Station. These operations cost estimates appear reasonable, given the implementation of a very different approach to human space operations than has been used for the Space Shuttle. This follows the recognition by the Operations Phase Assessment Team that the time criticality responsiveness associated with short duration Space Shuttle missions is not required for the

Space Station. However, there are always uncertainties in estimating logistics requirements until the hardware ground test program has been completed, flight experience gained and the problems encountered fixed. The reserve level of 25 percent appears appropriate in that regard.

The recommendations for revising the management and procurement approaches appear to offer the potential for significant cost savings, if implemented. There is political risk associated with radical change, and the potential for backsliding and politically necessary accommodations of the existing contract and management structure would undercut the estimates presented here. Timely implementation of the new management paradigm is assumed.

There are a variety of uncertainties inherent in the redesign process which effect the reliability of cost estimates. Not only are there the potential pitfalls identified immediately above, but also there is the potential of some high funding constraints. The experience of the Space Station Freedom over the past six years from the point of its design and development phase initiation is sobering. The 1987 estimates corrected the clear understatement of program costs initially presented to President Reagan and the American public in 1984, i.e., $8 billion for definition and development, expressed in 1984 economics. Those 1987 estimates projected a funding plan and a technical configuration that was never implemented. There is an underlying root cause of the almost annual budgetary reductions and the many program restructuring and redesigns: affordability. To the extent that the options presented in our report and their associated cost estimates are out of keeping with what the Administration and Congress believe is affordable in terms of annual budgets, the cost estimates will need to be appropriately revised.

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Option Assessment and Evaluation

Assessment Process

The assessment process provides a comparative measure of capability of the redesign options. The sequenced build-up of Space Station systems results in several "stopping points" for each option which are distinct potential Space Station configurations as shown in Table 43. The development phases are distinguished by the number of photovoltaic modules and the inclusion of pressurized laboratory volumes, habitation volumes, assured crew return capability and International Partner modules, as shown in Table 44. A capability assessment was performed for each development phase of each option with the premise that it was the final configuration of the Space Station. For Option A, only the Bus-1 configuration, Option A-1, was assessed. Option A-2 was not significantly different from Option B.

Each option is assessed against criteria derived from the Station Redesign Team require-

Table 43
Potential Space Station configurations

OPTION A	OPTION B	OPTION C
Power Station	Power Station	
Human Tended Capability	Human Tended Capability	Permanent Human Presence Capability
International Human Tended Capability	International Human Tended Capability	International Permanent Human Presence
Permanent Human Capability	Permanent Human Capability	Permanent Human Capability

Table 44
Development phase characteristics

CHARACTERISTIC	PS	HTC	IHTC	PHPC	IPHP	PHC
# OF PHOTOVOLTAIC MODULES	1	2	2-3	2	2	3
LABORATORY MODULE	NO	YES	YES	YES	YES	YES
HABITATION MODULE	NO	NO	NO	YES	YES	YES
ASSURED CREW RETURN	ORBITER	ORBITER	ORBITER	ACRV	ACRV	ACRV
INTERNATIONAL PARTNER MODULES	NO	NO	YES	NO	YES	YES

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Table 45
Research resource parameters

PARAMETERS	UNITS	REQUIREMENT	OPTION A1				OPTION B				OPTION C		
28.8 DEGREE INCLINATION		(REQ REF)	PS	HTC	IHTC	PHC	PS	HTC	IHTC	PHC	PHPC	IPHP	PHC
TOTAL NUMBER OF CREW	#	3,4(3.4,4.4)	4	4	4	4	4	4	4	4	4	4	4
TOTAL NUMBER OF RESEARCH CREW	#	2(1.1)	3+	3	3	3+	3+	3	2+	3+	3+	3+	3+
MAXIMUM CONTIGUOUS ON-ORBIT DAYS	DAYS	90(1.1)	20	20	20	365	20	20	20	365	365	365	365
TOTAL CREWED DAYS/YEAR	DAYS/YR		40	80	80	365	40	80	80	365	365	365	365
TOTAL AVAILABLE CREWHOURS/YEAR	HRS/YR		960	1920	1920	7680	960	1920	1920	7680	7680	7680	7680
TOTAL SYSTEMS CREWHOURS/YEAR	HRS/YR		50	415	476	956	50	471	550	1114	706	796	814
TOTAL RESEARCH CREWHOURS/YEAR	HRS/YR		910	1505	1444	6724	910	1449	1370	6566	6974	6884	6866
TOTAL POWER AVAILABLE (ORB AVG)	KW		23.1	23.1	46.1	57	23.5	23.5	68.3	68.3	57.6/34.2	54.9/34.2	62.9/46.5
SYSTEMS POWER (ORB AVG)	KW		15	16.1	28.1	26	11.4	15	27.7	28	11.7/11.1	22.7/22.1	22.7/22.1
USER POWER (ORB AVG)	KW	30(1.2)	8.1	7	18	31	12.1	8.5	40.6	40.3	45.9/23.1	32.2/12.1	40.2/24.4
30 DAY MAX. CONTINUOUS POWER	KW		18.5	18.5	39	45.8	19	19	59	59	53.4/29	50.4/23.3	58.4/31
POWER REGULATION	V+/-V		123+/-3	123+/-3	123+/-3	123+/-3	123+/-3	123+/-3	123+/-3	123+/-3	123+/-22	123+/-22	123+/-22
MAX. POWER TO SINGLE P/L @ μg<1	KW	12(1.3)	4.5(SL)	7	12	12	4.5(SL)	8.5	12	12	12	12	12
VOLTAGE LEVELS AVAIL. TO P/L	VDC,VAC	28,110(1.4)	28VDC(SL)	120VDC	120VDC	120VDC	28VDC(SL)	120VDC	120VDC	120VDC	120/28DC	120/28DC	120/28DC
TOTAL PRESSURIZED VOLUME	CUB M		93(SL)	110	491	760	93(SL)	219	680	878	736	1117	1117
NUMBER OF ISOLATABLE VOLUMES	#***		1(SL)	1	4	9	1(SL)	4	8	10	1	4	4
SYSTEM RACKS	#		2(SL)	7	31	59	2(SL)	12	41	65	24.5	49.5	49.5
USER RACKS	#	35 W/ IP(1.5)	8(SL)	9	39	39	8(SL)	16	48.5	45.5	40	70	70
UNITED STATES USER RACKS	#	11 @ HTC(1.5)	8(SL)	9	23	23	8(SL)	16	31	28	40	54	54
CENTRIFUGE ACCOMM. W/N VOLUME	Y/N- SIZE	YES-1.8M(1.6)	NO	NO	NO	YES-2.5	NO	NO	NO	YES-2.5	YES-2.5	YES-2.5	YES-2.5
USER RACKS @<1μg	#****	PDRD(1.8)	7(SL)	9/9	29/0	8	4(SL)	0/16	21/16	29/13	30	40	40
USER RACKS @<2μg	#****	PDRD(1.8)	8(SL)	9/9	39/14	36	8(SL)	10/16	38/31	45/28	40	72	72
OCCUPIED 30 DAY PERIODS AT LVLH	#		0	0	0	12	0	0	0	12	12	12	12
ACCELERATION MAPPING SYSTEM	Y/N	YES(1.9)	NO	YES	YES	YES	NO	YES	YES	YES	YES	YES	YES
OXYGEN LEVEL	%	21(1.7,2.15)	21(ORB)	21	21	21	21(ORB)	21	21	21	21	21	21
CO2 LEVEL	%	0.3	0.7(ORB)	0.52	0.52	0.6	0.7(ORB)	0.52,0.76	0.52,0.76	0.52	0.7	0.7	0.7
RELATIVE HUMIDITY	%	30-70(*)	30(ORB)	25-70	25-70	25-70	30(ORB)	25-70	25-70	25-70	30-70	30-70	30-70
CABIN PRESSURE	PSIA	14.7(*)	14.7(ORB)	14.7	14.7	14.7	14.7(ORB)	14.7	14.7	14.7	14.7	14.7	14.7
COMMUNICATION BANDS	TYPE		S	S, Ku	S, Ku	S, Ku, UHF	S	S, Ku	S, Ku, UHF	S, Ku, UHF	S, Ku	S, Ku	S, Ku
COMMUNICATION UPLINK	BPS	72K(1.17)	S-72K	S-72K			S-72K	S-72K			S-72K		
COMMUNICATION DOWNLINK	BPS	50M((1.15)	S-192K	S-192K, Ku-50M			S-192K	S-192K, Ku-50M			S-192K, Ku-50M		
VIDEO UPLINK/DOWNLINK	#CHANNELS	1/1(1.14/16)	0/0	0/4	0/4	0/4	0/0	0/4	0/4	0/4	0/2	0/2	0/2
VIDEO DOWNLINK COMPRESSION	#CHANNELS	6(1.14)	0	4	4	4	0	0	0	0	0	0	0
PAYLOAD VCR'S	#	4(1.18)	2(SL)	2	2	2	2(SL)	2	2	3	4	4	4
COMMUNICATION OUTAGE RECORDER	Y/N	YES(1.19)	YES(SL)	YES	YES	YES	YES(SL)	YES	YES	YES	YES	YES	YES
P/L DATA MANAGEMENT COMPUTER	Y/N	YES(1.11)	YES(SL)	YES	YES	YES	YES(SL)	YES	YES	YES	YES	YES	YES
ON BOARD DATA STORAGE	MBYTES		40	120	120	120	640	1280	1280	1280	441	441	441
TOTAL LINES OF CODE (NOT INCL. I.P.)	#		232K	405K	435K	492K	431K	1220K	1220K	1372K	232K	232K	232K
NITROGEN PURGE	Y/N	YES(1.24)	YES(SL)	YES	YES	YES	YES(SL)	YES	YES	YES	YES	YES	YES
VACUUM VENT LINES	Y/N	YES(1.26)	YES(SL)	YES	YES	YES	YES(SL)	YES	YES	YES	YES	YES	YES
POTABLE WATER	Y/N	YES(1.25)	NO(SL)	YES	YES	YES	NO(SL)	YES	YES	YES	YES	YES	YES
AIR/WATER PAYLOAD COOLING	Y/N	YES(1.29)	YES(SL)	YES	YES	YES	YES(SL)	YES	YES	YES	YES	YES	YES
EXTERNAL SITES	#	4(1.2)	4	4	14	14	1	4	15	15	3	13	13
EXTERNAL PAYLOAD POINTING	DIRECTION	N,R,W,Z(1.23)	N,R,W,Z	N,R,W,Z	N,R,W,Z	N,R,W,Z	N,R	N,R,W,Z	N,R,W,Z	N,R,W,Z	N,R,W,Z	N,R,W,Z	N,R,W,Z
OPTICAL WINDOWS	#-SIZE	1-20°(1.27)	0	1-8°	1-8°	1-8°	0	1-8°	1-8°	2-8°	4-8°	4-8°	4-8°
										2-20°	2-20°	2-20°	2-20°
TOTAL CREW	#	8(GG10,4.5)				8				8			8
TOTAL POWER	KW	75(GG10,4.5)				68				75			75

*Solar Inertial/LVLH

** Power regulation to 123+/-03V on some channels

***Does not include ACRV

****Without/With the Orbiter

*****0.3% CO2 is achievable on a periodic basis as required

******Acceleration vector rotates in Solar Inertial flight mode which may affect some microgravity expe ments. In particular, the research capability criteria directly reflect the task requirements as they flow down from the mission statement, objectives and strategies. Options are directly compared using key parameters which characterize the options. An assessment of capability is provided by a rated set of uniform evaluation criteria. Rating was performed by of the Station Redesign Team with support from the design centers.

Parameter Comparison

The following set of key parameters provides information for quick reference and comparison of options.

Research Resources

Table 45 provides the parameters related to research resources.

Crew and Duration: The total crew available for research for the Power Station and Human Tended Capability phases is constrained to four. This is based on a Space Shuttle crew of seven where the commander, pilot and a mission specialist are not available for Space Station tasks. In the Permanent Human Capability phase, the total number of crew is constrained to four on the basis of consumables and stowage limitations. All options provide more than three dedicated payload crew members except for Option B at International Human Capability which provides two dedicated crew members. Mission durations for the Power Station and Human Tended Capability phases are constrained to 20 days on the basis of crew health and safety considerations. Potential extension of Space Shuttle missions to 30 days is anticipated in the year 2000 but is treated as margin and not factored into the calculations of crew hours. The Power Station phases use Spacelab for research accommodations and are constrained to two missions per year due to the integration, test and verification schedule requirements of Spacelab. In the Human Tended Capability phases, laboratory volume is provided on the Space Station and the number of missions per year is increased to four. For Option A and Option B, continuous habitation of the Space Station is provided in the Permanent Human Capability phase. Option C provides continuous habitation in all phases. Available crew hours reflect an eight hour work day with the remaining time devoted to sleeping, eating, exercising and planning. In the Power Station and Human Tended Capability phases, the crew is provided with two days off in a 20 day mission. A five day work week with two days nonscheduled activities (catch-up, rest, etc.) is provided in the Permanent Human Capability phases, which assumes crew rotation at 90-day intervals.

Power: Power parameters are based on a "beginning-of-life" plus five years for the photovoltaic modules and batteries and include considerations of flight mode, articulation, architecture, orbital altitude, shadowing and battery depth-of-discharge. The 30-day maximum power parameter is provided to indicate the power available to support longer-duration research. The small gain in power for the addition of the third photovoltaic module for Option A, from Human Tended Capability to Permanent Human Capability, is an effect of array-to-array shadowing related to the articulation, configuration and flight mode.

Microgravity Levels: In the Power Station phases, payload racks are provided by and located in the Spacelab. The microgravity map of the Space Station changes with the orbiter present. This alters the number of payload racks located in a low microgravity area during tended and untended periods.

General: Figures 113, 114, and 115, illustrate the comparisons of each option as a function of available crew time, power, and volume over the ten year lifetime of the Space Station. Both Human Tended Capability options provide comparable crew hours and power levels per year. The Human Tended Capability option has delivered only one fifth of the capability provided by the Permanent Human Presence options at the end of the ten year defined Space Station life, Table 43. More significantly, the time on orbit limitations of both Option A and Option B Human Tended Capability phase precluded much of the longer duration physical and life sciences research.

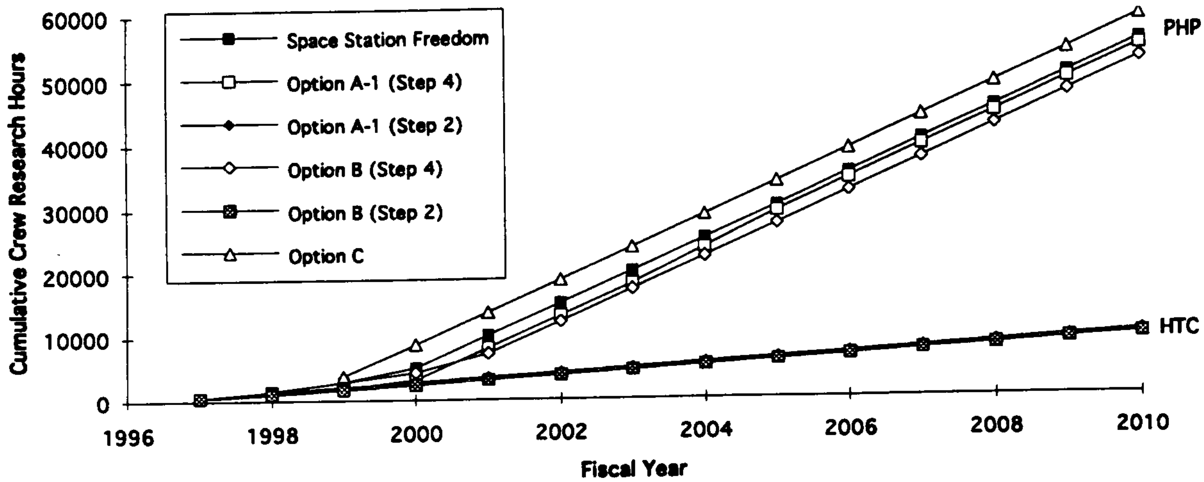

Figure 113
Station only research hours per fiscal year

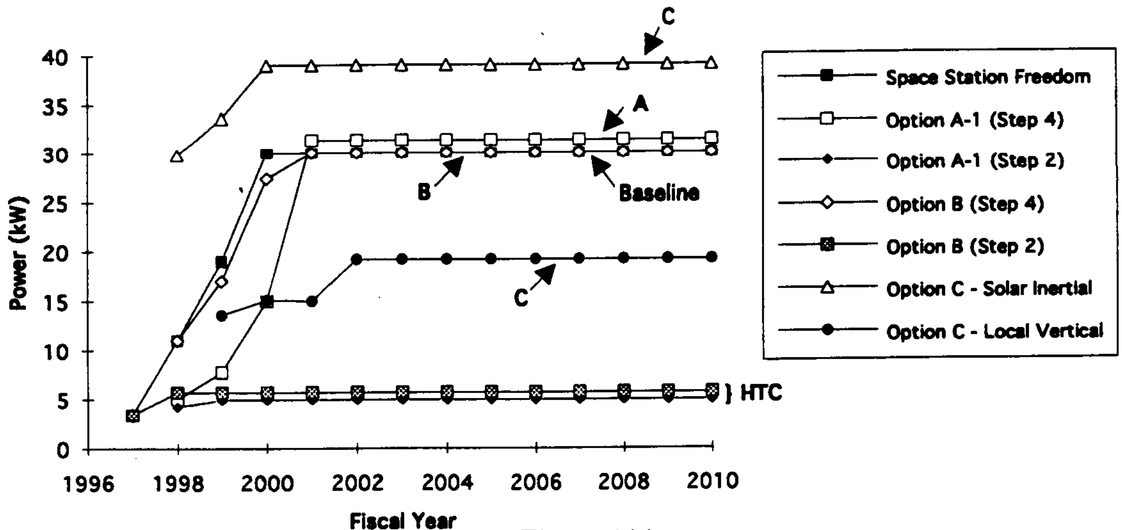

Figure 114
Station only power available to users

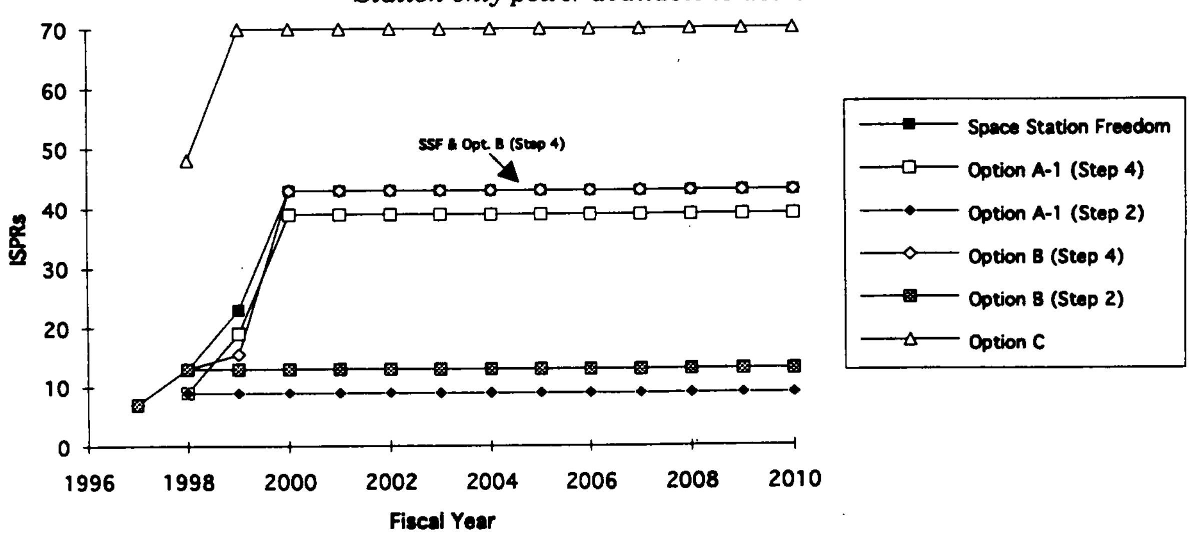

Figure 115
Station only internal volume available for research

Figure 114 shows the power comparisons over the same ten year period. Both Option A and Option B provide minimum power levels similar to the Space Station Freedom baseline. The two plots for Option C illustrate the significant fluctuations of power between the solar inertial and local-vertical local-horizontal attitudes.

Figure 115 illustrates the volume differences over time. The Human Tended Capability options are similar, and the Permanent Human Presence in Option A and Option B are relatively similar. Option C has more volume. The additional volume could reduce logistical flights to exchange facilities, provide more onboard storage, and provide for rapid commercial access.

Safety

Table 46 provides the parameters related to safety. Option B is single fault tolerant in the Power Station and Human Tended Capability phases due to the alpha joint configuration.

Assembly and Operations

Table 47 provides the parameters related to assembly and operations. In all options, the number of required logistics flights is reduced by the use of the advanced solid rocket motor when it becomes available in December 2000.

International Accommodation

Tables 48 and 49 provide the parameters related to the International Partner accommodation. Data are provided by the International Partners.

Option Assessment

Major factors which provide discrimination of capability were weighted and scored. Scoring was performed on a yellow-green-blue scale – poor, nominal, good (one-two-three rating) with blue (three) as the best score. A red score (zero) indicates the complete absence of a capability. Over 200 individual criteria were analyzed in evaluating the options. Those scores that have a poor (yellow) rating are discussed.

Research Capability

Table 50 summarizes the research capability assessment.

Option A: In the Power Station and Human Tended Capability phases, crew hours, payload

Table 46
Safety parameters

PARAMETERS	UNITS	REQUIREMENT	OPTION A1				OPTION B				OPTION C		
28.8 DEGREE INCLINATION		(REQ REF)	PS	HTC	IHTC	PHC	PS	HTC	IHTC	PHC	PHPC	IPHP	PHC
STATION CRITICAL	LEVEL	2(TAB 2.1)	2	2	2	2	1	1	2	2	2	2	2
STATION SURVIVAL	LEVEL	2(TAB 2.1)	2	2	2	2	1	1	2	2	2	2	2
CREW SURVIVAL	LEVEL	2(TAB 2.1)	2(ORB)	2	2	2	2(ORB)	2(ORB)	2	2	2	2	2
CREW HEALTH CARE SYSTEMS	LEVEL	1(TAB 2.1)	1(ORB)	1(ORB)	1(ORB)	1	1(ORB)	1(ORB)	1	1	1	1	1
SAFE HOLD	YRS	2(2.29)	3	3	3+	3+	2+	2+	2+	2+	2	2	2
SAFE HAVEN	TYPE		N/A	N/A	N/A	ACRV	N/A	N/A	N/A	NODES	ACRV	ACRV	ACRV
CREW ESCAPE	Y/N	YES(2.6)	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
ACRV	#-TYPE	(2.8)	1-ORBITER	1-ORBITER	1-ORBITER	2-SOYUZ	1-ORBITER	1-ORBITER	1-ORBITER	2-SOYUZ	2-SOYUZ	2-SOYUZ	2-SOYUZ
FIRE DETECTION	AUTO/MAN	(2.7)	AUTO(ORB)	AUTO	AUTO	AUTO	AUTO(ORB)	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO
FIRE SUPRESSION	AUTO/MAN	(2.7)	MAN(ORB)	AUTO/MAN	AUTO/MAN	AUTO/MAN	MAN(ORB)	AUTO/MAN	AUTO/MAN	AUTO/MAN	AUTO/MAN	AUTO/MAN	AUTO/MAN
STAN. CAUTION AND WARNING SYS.	Y/N	YES(1.13,2.6)	YES(ORB)	YES	YES	YES	YES(ORB)	YES	YES	YES	YES	YES	YES
CREW MANUAL OVERRIDES OF CRIT. SYS.	Y/N	YES(2.5)	YES(ORB)	YES	YES	YES	YES(ORB)	YES	YES	YES	YES	YES	YES
MMOD 10 YEAR PROBABILITY	*	0.9955	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
DMS CORE CRIT. FUNCTIONS PARTITIONED	Y/N	YES(2.14)	YES(ORB)	YES	YES	YES	YES(ORB)	YES	YES	YES	YES	YES	YES

* Requirement is under review and is discussed in Issue section of report

Table 47
Assembly and operations parameters

PARAMETERS	UNITS	REQUIREMENT	OPTION A1				OPTION B				OPTION C		
28.8 DEGREE INCLINATION		(REQ REF)	PS	HTC	IHTC	PHC	PS	HTC	IHTC	PHC	PHPC	IPHP	PHC
ASSEMBLY													
CUMM ASSEMBLY/OUTFITTING FLIGHTS	#		3	4	12	16	2	8	17	20	4	8	9
LAUNCH VEHICLE	TYPE		SHUTTLE	SHUTTLE	SHUTTLE	SHUTTLE	SHUTTLE	SHUTTLE	SHUTTLE	SHUTTLE	SLCS/SH	SHUTTLE	SHUTTLE
CUMMULATIVE ASSEMBLY EVA	MANHRS		40	64	154	224	44	159	294	311	0	12	24
OPERATIONS													
NUMBER OF LOGISTICS FLIGHTS	FLTS/YR		0-1	1-2	2-3	6*	0-1	1-2	1-2	6*	5	6*	6*
OPERATIONS CREW HOURS	MANHRS/YR		14	122	134	226	14	122	134	226	226	249	249
MAINTENANCE CREW HOURS EVA/IVA	MANHRS/YR		36/0	125/168	143/199	187/543	36/0	175/174	193/223	253/635	50/430	68/479	80/485
ORBITER MATING CAPABILITY	SNGL/DUAL	DUAL(2.23)	SINGLE	SINGLE	SINGLE	DUAL	SINGLE	DUAL	SINGLE	SINGLE	DUAL	DUAL	DUAL
MOBILE TRANSPORTER	Y/N		NO	NO	NO	NO	YES	YES	YES	YES	NO	NO	NO
ON-ORBIT DATA DISPLAY	Y/N	YES(3.5)	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
PAYLOADS OPERABLE UNOCCUPIED	Y/N		YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
STATION OPERABLE UNOCCUPIED	Y/N		YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
NOTES													
*Logistics flights reduce by one flight per year when the ASRM becomes available													

power and microgravity durations during tended periods do not meet the Science, Technology and Engineering Research Design Guidelines. The available payload power is limited in these phases during tended operations due to the parasitic power demands of the orbiter when it is docked. Power availability is increased 100 percent during untended operation. Option A does not provide as much power as Option B due to differences in the electrical power system configuration and is approximately 10 percent below the requirement at Permanent Human Capability. In the Power Station phase, payload volume is provided by the Spacelab which is not expected to be utilized for the Human Tended Capability phases due to the presence of a laboratory module. The payload volume of the laboratory module is limited and less than the laboratory module in Option B. Payload volume becomes adequate in the International Human Tended phase and is increased in the Permanent Human Capability phase. During the Human Tended Capability phases the microgravity levels are met in 85 percent of the core module racks during untended operations, without the orbiter docked, but during tended operations no payload volumes are within the required microgravity levels. At the Permanent Human Capability phase, 10 percent of the racks in the core module, 45 percent of the racks in the Japanese Experiment Module , and no racks in the Columbus Attached Pressurized Module are within microgravity levels that meet the requirements. The entire station rolls periodically to achieve the best power generation. The time between station maneuvers varies between seven and 59 days. Experiments which are sensitive to both the magnitude and direction of accelerations will require specific scheduling with consideration of flight orientation and manuevers. Vehicle manuevers may also adversely affect up to 65 percent of the expected exposed technology payloads mounted to external attach points and the Japanese Experiment Module Exposed Facility. No optical quality windows, equipment airlock, or video coverage of external attach points for support of engineering research are provided in the Power Station phase. The size of the optical window provided at the Human Tended Capability phase restricts its usefulness for sensor development. An automated equipment airlock is provided with the Japanese Experiment Module in the International Human Tended Capability phase.

Option B: The restricted capability of the Power Station and Human Tended Capability phases is similar to Option A. Option B provides three photovoltaic modules at the International Human Tended Capability phase which results in more available payload power. The electrical power system configuration, with both alpha and beta gimbals, provides sufficient payload power at the Permanent Human Capability phase. These gimbals also eliminate any need for vehicle manuevers for increased power generation

Table 48
Japanese Experiment Module and Columbus Attached Pressurized Module parameters

PARAMETERS	UNITS	REQUIREMENT	OPTION A1		OPTION B		OPTION C	
28.8 DEGREE INCLINATION		REQ (PARA)	IHTC	PHC	IHTC	PHC	IPHP	PHC
JEM ACCOMMODATION								
[illegible]								
DEVELOPMENT COST ADHERENCE	H/M/L	HIGH	M	M	M	M	L	L
OPERATIONS COST SAVINGS	H/M/L	HIGH	H	H	M	M	M	M
SCHEDULE ADHERENCE	H/M/L	HIGH	H	H	M	M	L	L
[illegible]								
SYSTEM POWER (CREW/NO CREW)	kW/kW	5.7/4	5.7/4	5.7/4	5.7/4	5.7/4	5.7/4	5.7/4
USER POWER (MAX./YEARLY AVG.*)	kW/kW	14/3.84	14/2.9	14/4	14/3.8	14/4.9	14/2.5	14/2.5
JEM RACKS (TOTAL/RACKS @ <1μg)	#/#	10/5	10/5	10/5	10/5	10/5	10/1	10/1
JEM EF P/L (TOTAL/SITES @<1μg)	#/#	10/5	10/2	10/2	10/5	10/5	10/1	10/1
DATA COMM. (UPLINK/DOWNLINK)	KBPS/MBPS	72/50	72//50	72/50	72/50	72/50	72/50	72/50
[illegible]								
MODULE INTEGRITY	H/M/L	HIGH	M	H	H	H	L	L
EF PAYLOAD VIEWING (NADIR/ZENITH)	H/M/L	HIGH/HIGH	M/M	M/M	H/H	H/H	-/L	-/L
[illegible]								
EPS	H/M/L	HIGH	H	H	H	H	L	L
ECLSS	H/M/L	HIGH	H	H	H	H	L	L
TCS	H/M/L	HIGH	M	M	H	H	L	L
DMS	H/M/L	HIGH	M	M	H	H	L	L
AUDIO/VIDEO	H/M/L	HIGH	M	M	H	H	L	L
CAUTION AND WARNING	H/M/L	HIGH	M	M	H	H	L	L
[illegible]								
OPERATIONS IMPROVEMENT	H/M/L	HIGH	H	H	M	M	L	L
VERIFICATION APPROACH	H/M/L	HIGH	H	H	H	H	L	L
RISK CONTROL	H/M/L	HIGH	H	H	M	M	L	L
APM ACCOMMODATION								
[illegible]								
DEVELOPMENT COST ADHERENCE	H/M/L	HIGH	M	M	H	H	L	L
OPERATIONS COST SAVINGS	H/M/L	HIGH	H	H	M	M	M	M
SCHEDULE ADHERENCE	H/M/L	HIGH	H	H	M	M	H	H
[illegible]								
SYSTEM POWER (CREW/NO CREW)	kW/kW	5.9/3.7	5.9/3.7	5.9/3.7	5.9/3.7	5.9/3.7	3/3	5.9/3.7
USER POWER (MAX./YEARLY AVG.*)	kW/kW	12/3.84	/3.6	12/3.84	12/3.84	12/3.84	/2.4	12/3.84
RACKS (TOTAL/RACKS @ <7μg)	#/#	21/11	11/11	11/11	11/11	11/11	11/11	11/11
DATA COMM. (UPLINK/DOWNLINK)	KBPS/MBPS	72/50	72/50	72/50	72/50	72/50	72/50	72/50
[illegible]								
MODULE INTEGRITY	H/M/L	HIGH	M	H	M	H	L	L
[illegible]								
EPS	H/M/L	HIGH	H	H	H	H	L	L
ECLSS	H/M/L	HIGH	H	H	H	H	L	L
TCS	H/M/L	HIGH	M	M	H	H	L	L
DMS	H/M/L	HIGH	M	M	H	H	M	M
AUDIO/VIDEO	H/M/L	HIGH	M	M	H	H	M	M
EMADS	H/M/L	HIGH	H	H	H	H	L	L
OPERATIONS/VERIFICATION								
OPERATIONS IMPROVEMENT	H/M/L	HIGH	H	H	M	M	L	L
VERIFICATION APPROACH	H/M/L	HIGH	H	H	H	H	L	L
RISK CONTROL	H/M/L	HIGH	M	M	H	H	L	L

Table 49
Internationl Partners Mobile Servicing Structure parameters

PARAMETERS	UNITS	REQUIREMENT	OPTION A1				OPTION B				OPTION C		
28.8 DEGREE INCLINATION		REQ (PARA)	PS	HTC	IHTC	PHC	PS	HTC	IHTC	PHC	PHPC	IPHP	PHC
COMPLIANCE WITH BASELINE	H/M/L	SSP30000	M	M	M	M		H	H	H	L	L	L
COST COMPLIANCE	H/M/L	$1.35B	L	L	L	L	M	M	M	M	L	-L	L
SCHEDULE COMPLIANCE	MONTHS	8/96	+21					+15			+25		
MSS DEV. AND IT&V COMPLIANCE	H/M/L	SSP30651	L	L	L	L	H	H	H	H	L	L	L
ASS'Y WITH SRMS W/I DESIGN LIMITS	YES/NO		NO	NO	NO	NO	-	-	-	-	-	-	-
SSRMS	YES/NO	YES	YES	YES	YES	YES		YES	YES	YES	YES	YES	YES
SPDM	YES/NO	YES		NO	YES	YES		NO	YES	YES	YES	YES	YES
MBS	YES/NO	YES		NO	NO	NO		NO	YES	YES	NO	NO	NO
MT	YES/NO	YES	NO	NO	NO	NO	YES	YES	YES	YES	NO	NO	NO
MMD	YES/NO	YES		NO	NO	NO		NO	YES	YES	NO	NO	NO
MSS WORKSTATION (NASA SUPPLIED)	YES/NO	3 XMPAC	NO	NO	NO	NO		YES	YES	YES	NO	NO	NO
MSS LAUNCH FSE/STOWAGE	YES/NO	YES	NO	NO	NO	NO		YES	YES	YES	NO	NO	NO
CUPOLA	YES/NO-#	YES-2			YES-1	YES-1		-	YES	YES	NO	NO	NO
MSS MAINTENANCE FEASIBILITY	YES/NO		NO	NO	NO	NO		NO	YES	YES	NO	NO	NO
POWER(PEAK/KEEPALIVE)	kW	5.4/1.2	2/0.5	2/0.5	5.4/1.2	5.4/1.2		2/0.5	5.4/1.2	5.4/1.2	TBD	TBD	TBD
PAYLOAD RACKS	#	1.5	0	0	1.5	1.5		0	1.5	1.5	1.5	1.5	1.5
CREW ALLOCATION	MO/YR	1.5+	0	0	1.5	1.5		0	1.5	1.5	1.5	1.5	1.5
EPS	H/M/L	SSP30263		H	H	H		H	H	H	L	L	L
C&T	H/M/L	SSP30260	M	M	M	M		M	M	M	M	M	M
DMS	H/M/L	SSP30261	L	L	L	L		H	H	H	L	L	L
MSS-TO-P/L INTERFACE	H/M/L	SSP42004	M	M	M	M		H	H	H	M	M	M
CSA/NASA DESIGN RESPONSIBILITY	+/-	SSP30651	+CSA	+CSA	+CSA	+CSA					+CSA	+CSA	+CSA
SSRMS/SPDM DUTY CYCLE	%	15-20			30-40	40-40		15-20	15-20	15-20	<5	<10	<10
ROBOTICS OPS CONCEPT COMPLIANCE	H/M/L	IOS	L	L	L	L		H	H	H	M	M	M
QUANTITY OF ORU'S ROBOT. SERVICABLE	#	306	TBD	TBD	TBD	260		300	300	300	<100	<100	<100
GROUND CONTROL CAPABILITY	YES/NO	YES	YES	YES	YES	YES		YES	YES	YES	YES	YES	YES
STN EXTERNAL LIGHTS AND CAMERAS	#	7	TBD	4	4	4		4	4	4	8 LGHTS	8 LGHTS	8 LGHTS

Table 50
Research capability assessment summary

ASSESSMENT CRITERIA	OPTION A				OPTION B				OPTION C		
28.8 DEGREE INCLINATION	PS	HTC	IHTC	PHC	PS	HTC	IHTC	PHC	PHPC	IPHP	PHC
CREW NUMBER	2	2	2	2	2	2	2	2	2	2	2
MISSION DURATION	1	1	1	3	1	1	1	3	3	3	3
POWER	2	2	1	1	2	2	2	2	2	2/1	2/1
VOLUME	1	1	2	3	1	1	2	3	3	3	3
MICROGRAVITY LEVELS/DURATION	1	2/1	2/1	1	1	1/2	1	2	1/3	1/3	1/3
CABIN ENVIRONMENT	2	2	2	2	2	2	2	2	2	2	2
RESEARCH RESOURCES	2	2	2	2	2	2	2	2	2	2	2
DATA AND COMMUNICATION	1	2	2	2	1	2	2	2	2	2	2
OPTICAL WINDOWS	1	2	2	2	1	2	2	2	3	3	3
EXTERNAL PAYLOAD ACCOMMODATION	1	1	2	2	2	2	2	2	1	1	1
ENGINEERING RESEARCH ACCOMMODATION	1	2	3	3	1	2	3	3	2	3	3
PAYLOAD GROWTH POTENTIAL	2	2	2	2	2	2	2	2	2	2	2
LEGEND	1-	Poor	2-	Nominal	3-	Good					

Note: Option A and B Microgravity levels/duration shown for untended/tended (left/right)

Note: Option C power and microgravity level shown for SI/LVLH (left/right) thereby maintaining relatively constant magnitudes and directions of accelerations. External payloads are similarly benefitted by the lack of required vehicle manuevers. Unlike Option A, the laboratory microgravity levels are better during tended operation with the orbiter attached and become significantly worse in the untended configuration. The laboratory module provides sufficient volume for payloads beginning with the Human Tended Capability phase. At the Permanent Human Presence phase, the optical windows provided accommodate sensor development research. As it is in Option A, an automated equipment airlock is provided with the Japanese Experiment Module in the International Human Tended Capability phase.

Option C: This option provides permanent presence in all phases which results in adequate missions lengths, crew hours and durations of tended microgravity research. Option C provides two flight modes, solar-inertial and local-vertical local-horizontal. The solar-inertial flight mode provides maximum payload power. However, the solar inertial flight mode may induce undesirable accelerations for some research experiments and does not accommodate external attached payloads that require ram and wake measurements and constant pointing directions. However, a system consisting of low-thrust propulsion jets and a device for sensing acceleration was used in 1972 to counter drag on Stanford University's drag Free satellite; a similar system is been considered for Option C. This system could potentially improve the desired microgravity environment while in the solar inertia flight mode. The local-vertical local-horizontal flight mode, which is preferred for some high priority microgravity research, such as electronic and photonic crystal growth and fluid physics and combustion, does not provide as much power to the payloads. In the local-vertical local-horizontal flight mode, the station rotates to maintain power generation due to the absence of beta gimbals on the solar arrays. Time sharing methodologies for payloads may be employed to accommodate different research disciplines that are better served by the different flight modes. Power regulation reduction in station electrical power system requires conditioning equipment to be provided by the individual payloads, if required. Option C also provides substantial payload volume and racks with the capability of accommodating a large centrifuge.

International Accommodation

Table 51 provides a summary of the international accommodation assessment.

Option A: The design maintains a high level of compliance with the Intergovernmental Agreement and the Memoranda of Understanding for the Japanese Experiment Module and the Attached Pressurized Module elements, in particular in the Permanent Human Capability phase. There are only changes in the data management system and communication and tracking systems interface to the Japanese Experiment Module and Attached Pressurized Module elements. The roles of the International Partners for the Japanese Experiment Module and Attached Pressurized Module elements as major contributors of payload accommodations for the international users are retained. Option A provides the earliest opportunities for Japanese Experiment Module and Attached Pressurized Module element launches. The power available to payloads is reduced for the Japanese Experiment Module and Attached Pressurized Module elements.

The accommodation of the Mobile Servicing System elements in Option A is rated low overall. The lack of a Mobile Servicing System Mobile Transporter significantly degrades the Mobile Servicing System role and negatively impacts compliance to the Intergovernmental Agreement and the Memoranda of Understanding for the Mobile Servicing System element. Changes to the data management system interfaces and the deletion of robotics workstations with related video systems, impact the end-to-end command and control system architecture and consequently the cost of the Mobile Servicing System element. The Mobile Servicing System element is launched later than agreed to. The payload resources for racks and power to the Canadian Space Agency are reduced.

Option B: This option maintains a high level of compliance to the Intergovernmental Agreement and the Memoranda of Understanding for the Japanese Experiment Module, Attached Pressurized Module, and Mobile Servicing System elements in International Human Tended Capability phase and the Permanent Human Capability phase. There are only minor changes in the data management system and communication and tracking systems interface to the Japanese

Table 51
International accommodation assessment summary

ASSESSMENT CRITERIA	OPTION A				OPTION B				OPTION C		
28.8 DEGREE INCLINATION	PS	HTC	IHTC	PHC	PS	HTC	IHTC	PHC	PHPC	IPHP	PHC
APM ACCOMMODATION	0	0	3	3	0	0	2	2	0	1	1
• COMPLIANCE WITH IGA/MOU	0	0	2	3	0	0	2	3	0	1	1
• INTERFACES IMPACT	0	0	3	3	0	0	2	2	0	1	1
• CONTINUITY OF ROLES	0	0	3	3	0	0	3	3	0	1	1
• DEVELOPMENT COST IMPACT	0	0	3	3	0	0	3	3	0	1	1
• OPERATIONS COST IMPACT	0	0	3	3	0	0	2	2	0	2	2
• SCHEDULE IMPACT	0	0	2	2	0	0	3	3	0	1	1
• PAYLOAD RESOURCES IMPACT	0	0	2	3	0	0	2	3	0	1	2
JEM ACCOMMODATION	0	0	2	2	0	0	2	2	0	1	1
• COMPLIANCE WITH IGA/MOU	0	0	2	3	0	0	2	3	0	1	1
• INTERFACES IMPACT	0	0	2	2	0	0	2	2	0	1	1
• CONTINUITY OF ROLES	0	0	3	3	0	0	3	3	0	1	1
• DEVELOPMENT COST IMPACT	0	0	2	2	0	0	2	2	0	1	1
• OPERATIONS COST IMPACT	0	0	3	3	0	0	2	2	0	2	2
• SCHEDULE IMPACT	0	0	3	3	0	0	2	2	0	1	1
• PAYLOAD RESOURCES IMPACT	0	0	1	2	0	0	2	3	0	1	1
MSS ACCOMMODATION	1	1	1	1	1	1	2	3	1	2	2
• COMPLIANCE WITH IGA/MOU	1	1	1	2	1	1	2	3	1	2	2
• INTERFACES IMPACT	1	1	1	1	1	1	2	2	1	1	1
• CONTINUITY OF ROLES	1	1	2	2	1	1	3	3	1	2	2
• DEVELOPMENT COST IMPACT	1	1	1	1	1	1	2	2	1	1	1
• OPERATIONS COST IMPACT	1	1	1	1	1	1	2	3	2	2	2
• SCHEDULE IMPACT	1	1	1	1	1	1	2	2	1	1	1
• PAYLOAD RESOURCES IMPACT	1	1	2	2	1	1	2	3	2	2	3
MPLM ACCOMMODATION	0	3	2	2	0	3	2	3	2	2	2
• COMPLIANCE WITH IGA/MOU	0	3	2	2	0	3	2	3	2	2	2
• INTERFACES IMPACT	0	3	3	3	0	3	3	3	2	2	2
• CONTINUITY OF ROLES	0	3	2	2	0	3	2	3	2	2	2
• DEVELOPMENT COST IMPACT	0	3	2	2	0	3	3	3	2	2	2
• OPERATIONS COST IMPACT	0	2	2	2	0	3	2	2	2	2	2
• SCHEDULE IMPACT	0	2	2	2	0	2	2	2	1	1	1
• PAYLOAD RESOURCES IMPACT	0	2	2	2	0	3	3	3	3	2	2
RUSSIAN PARTICIPATION	1	1	1	1	1	1	1	1	1	1	1
• HUMAN ACCESS	1	1	1	1	1	1	1	1	1	1	1
• CARGO ACCESS	1	1	1	1	1	1	1	1	1	1	1
• ACRV	1	1	2	2	1	1	1	2	2	2	2
• ECLSS SUBSYSTEM	1	1	1	1	1	1	1	1	1	1	1
• DOCKING SUBSYSTEM	1	2	2	2	1	2	2	2	2	2	2
LEGEND	0-	Non-existent		1-	Poor	2-	Nominal	3-	Good		

Experiment Module, Attached Pressurized Module, and Mobile Servicing System elements. The roles of the International Partners for the Japanese Experiment Module and Attached Pressurized Module elements as major contributors of payload accommodations for the international users are retained. The role of the Canadian Space Agency in assembly and maintenance of the Space Station is retained. Option B maintains the level of payload resources available to the International Partners.

Option C: The configuration is not consistent with the current Intergovernmental Agreement and Memoranda of Understanding with the International Partners. A red (zero) rating was assessed by NASDA for lack of compliance with the Intergovernmental Agreement and Memoranda of Understanding. Also, the International Partners assessed the continuity of their roles as absent in Option C and therefore rated this element as red (zero). This rating is inconsistent with the rating guidelines where red (zero) is intended to indicate items which are nonexistent. Participation of the International Partners in Option C is accommodated in the configuration and therefore this rating was changed to yellow (one).

Changes to the core systems for power and data have impacts on the Japanese Experiment Module, Columbus Attached Pressurized Module, and Mobile Servicing System element interfaces. Payload power and availability of low microgravity environments for the Japanese Experiment Module and Attached Pressurized Module elements are reduced. The field of view for the Japanese Experiment Module Exposed Facility is limited in Option C.

For all options, Russian participation is limited to the provision of a Soyuz and Mir docking system for assured crew return at the 28.8 degree inclination.

Operations

Table 52 provides a summary of the operations assessment.

Options A and B: Option A and Option B operations are rated nominal overall for all phases except Permanent Human Capability. On-orbit operations for the Option A Power Station are simplified by the existing Bus-1 control center support facilities. Ground operations for the Power Station phase of Option A and Option B are simplified due to the relatively small number of system elements requiring processing and test and verification. In the International Human Tended Capability and Permanent Human Capability phases, assembly extravehicular activity, ground system processing and verification, maintenance and training become more complicated consistent with the increased number of launches. In Option A, maintenance extravehicular activity operations are impacted by the complexity of the mobility paths and reduction of translational aids and for field of view. Both Options A and B indicate that a large backlog of maintenance actions will accumulate prior to Permanent Human Capability. This may be mitigated by taking advantage of additional EVA time inherent on the shuttle flights or by the scheduling of a maintenance flight for phases prior to permanent occupation.In both Option A and Option B, continuous occupation of the Space Station in the Permanent Human Capability phase eliminates the backlog and hence crew time for maintenance and operations is proportionally reduced.

Table 52
Operations assessment summary

ASSESSMENT CRITERIA	OPTION A				OPTION B				OPTION C		
28.8 DEGREE INCLINATION	PS	HTC	IHTC	PHC	PS	HTC	IHTC	PHC	PHPC	IPHP	PHC
ASSEMBLY	2	2	1	1	2	2	1	1	3	3	3
GROUND OPERATIONS	3	2	1	1	3	2	1	1	3	2	2
ON-ORBIT OPERATIONS	3	2	2	2	2	2	2	2	2	2	2
MAINTENANCE	2	2	2	1	2	2	1	2	3	3	3
LOGISTICS	2	2	2	2	2	2	2	1	3	2	2
TRAINING	3	2	2	1	3	2	2	1	3	2	2
FACILITIES	2	2	2	1	2	2	2	1	1	1	1
LEGEND	1-	Poor	2-	Nominal	3-	Good					

Option C: Option C operations are rated high for the Permanent Human Capability phase and nominal for all other phases. The use of Space Shuttle subsystems provides advantages in spares commonality, logistics and training. The single launch core element simplifies assembly and ground operations in the Permanent Human Capability phase. The extravehicular activity requirements for maintenance are significantly reduced for all phases due to reduced external systems. Changes to the Vehicle Assembly Building and launch pad are required for the single launch vehicle in Option C.

All options require new facilities for processing the Soyuz assured crew return vehicle.

Engineering

Table 53 provides a summary of the engineering assessment.

Options A and B: For Option A and Option B, crew systems during the Power Station and Human Tended Capability phases are provided by the orbiter. For the Permanent Human Capability phases, crew systems are improved with regard to stowage, crew quarters, and accommodations. In Option A, the Bus-1 propulsion system provides a simple and efficient propulsion system design. The maintenance of the guidance, navigation and control system is difficult for the Bus-1 in Option A. Option B differs from Option A in that the photovoltaic modules include both alpha and beta gimbals for maximum power performance.

Option C: In Option C, the electrical power system generates less power in the preferred microgravity flight mode. Reduced power regulation and isolation of loads is provided in the Permanent Human Presence Capability phase and the International Permanent Human Presence phase of Option C. The data management system is limited in flexibility with regard to command, display and interoperability performance. The body mounted radiators do not require articulation and are preintegrated on the ground.

Development Risk

Table 54 provides a summary of the development risk assessment.

Options A and B: For Option A, the development risk in the propulsion and guidance, navigation, and control systems is reduced by utilizing the flight proven Bus-1 system. For Option A and Option B, the crew systems development risk in the Power Station and Human Tended Capability phases is reduced due to the use of proven Space Shuttle systems. For the Permanent Human Capability phase, some new crew systems are provided or modified that have nct been flight proven.

The integrated systems risk in Option C is significantly reduced due to the larger assembly margins and verification efficiencies provided by integration on the ground rather than on-orbit. An exception to this is the electrical power sys-

Table 53
Engineering assessment summary

ASSESSMENT CRITERIA	OPTION A				OPTION B				OPTION C		
28.8 DEGREE INCLINATION	PS	HTC	IHTC	PHC	PS	HTC	IHTC	PHC	PHPC	IPHP	PHC
INTEGRATED SYSTEM PERFORMANCE	2	3	2	2	2	3	2	2	3	2	2
DMS DESIGN PERFORMANCE	2	2	2	2	2	2	2	2	2	1	1
EPS DESIGN PERFORMANCE	2	2	2	2	3	3	3	3	1	1	1
TCS DESIGN PERFORMANCE	2	2	2	2	2	2	2	2	3	2	2
ECLSS DESIGN PERFORMANCE	2	3	3	3	2	3	3	3	2	2	2
GNC DESIGN PERFORMANCE	2	2	2	2	3	3	3	3	3	3	2
C&T DESIGN PERFORMANCE	2	2	2	2	2	2	2	2	2	2	2
PROPULSION DESIGN PERFORMANCE	3	3	3	3	2	2	2	2	2	2	2
STRUCTURE DESIGN PERFORMANCE	2	2	2	2	2	2	2	2	3	3	3
CREW SYSTEMS DESIGN PERFORMANCE	2	2	2	3	2	2	2	3	3	3	3
LEGEND	1-	Poor	2-	Nominal	3-	Good					

Table 54
Development risk assessment summary

ASSESSMENT CRITERIA	OPTION A				OPTION B				OPTION C		
28.8 DEGREE INCLINATION	PS	HTC	IHTC	PHC	PS	HTC	IHTC	PHC	PHPC	IPHP	PHC
INTEGRATED SYSTEM RISK	2	2	2	2	2	2	2	2	3	3	3
DMS RISK	3	2	2	2	2	2	2	2	3	2	2
EPS RISK	3	3	3	3	3	3	3	3	1	1	1
TCS RISK	2	2	2	2	2	2	2	2	2	2	2
ECLSS RISK	2	2	2	2	2	2	2	2	2	2	2
GNC RISK	3	3	3	3	2	2	2	2	2	2	2
C&T RISK	2	2	2	2	2	2	2	2	2	2	2
PROPULSION RISK	3	3.	3	3	2	2	2	2	2	2	2
STRUCTURE RISK	3	2	2	2	2	2	2	2	2	2	2
CREW SYSTEMS RISK	3	2	2	1	3	2	2	1	3	3	3
LEGEND	1 -	Poor	2 -	Nominal	3 -	Good					

tem which, due to the absence of isolation devices, is not completely verifiable on the ground. The core module structural design is new for Option C, but is based on the flight proven design and manufacturing of the external tank. The crew systems risk is reduced through the use of mostly proven Space Shuttle systems.

Safety and Reliability

All three options have increased reliability over the baseline program by incorporating a SAFE MODE, which is executed in the avionics systems, to automatically switch to redundant components or take the vehicle to a stabilized attitude to assure shuttle docking capability.

Table 55 provides a summary of the safety and reliability assessment.

The capability of the Bus-1 propulsion system provides Option A with substantial capability for a safe hold. By carrying electrical and thermal system services across the alpha joint, Option B is single fault tolerant in the Power Station and Human Tended phases and does not meet the requirement for two fault tolerance for station critical, station survival and crew survival functions.

Safety and reliability exhibit similar trades across the options. Option B and to a lesser degree, Option A, are characterized by risk associated with a significant number of extravehicular activities for repairing items on the truss. Option C requires very little extravehicular activities, as most of its components are within the core pressurized volume. On the other hand, due to its open design, Option C has little ability to contain fire, smoke, fumes, spills or air leaks in the core station while Option B has reasonable containment and safe haven features. These pros and cons result in nominal overall rankings for all three designs.

Table 55
Safety and reliablity assessment summary

ASSESSMENT CRITERIA	OPTION A				OPTION B				OPTION C		
28.8 DEGREE INCLINATION	PS	HTC	IHTC	PHC	PS	HTC	IHTC	PHC	PHPC	IPHP	PHC
FAULT TOLERANCE	2	2	2	2	1	1	2	2	2	2	2
SAFETY SYSTEMS	2	2	2	2	2	2	2	2	2	2	2
RELIABILITY	2	2	2	2	2	2	2	2	2	2	2
LEGEND	1 -	Poor	2 -	Nominal	3 -	Good					

Table 56
Parameter comparison for inclinations 28.8 and 51.6 degrees

PARAMETERS	UNITS	OPTION A1		OPTION B		OPTION C	
		PHC		PHC		PHC	
INCLINATION		28.8	51.6	28.8	51.6	28.8	51.6
COST (1994-1998)	$B	13.3	13.5	13.3	13.6	11.9	12.1
SCHEDULE	MO/YR	9/00	9/00	12/01	3/02	1/01	11/01
TOTAL POWER AVAILABLE (ORB AVG)	kW	57	68	68.3	68.4	62.9/46.5	64.9/54.9
TOTAL USER POWER (ORB AVG)	kW	31	41.2	40.3	40.4	40.2/24.4	42.2/32.8
MAX. CONT. 30 DAY AVAILABLE POWER	kW	45.8	45.9	59	59	58.4/31	58.4/31
# OF ASSEMBLY/OUTFITTING FLIGHTS	#	16	16	20	22	9	11
Al-Li ET	YES/NO	NO	YES	NO	YES	NO	YES
ASSEMBLY EVA REQUIRED	CREW HRS	224	224	311	311	24	24
NUMBER OF LOGISTICS FLIGHTS	FLTS/YR**	6	7	6	7	5	6
CARGO ACCESS (IN ADD'N TO SHUTTLE)	VEHICLE***	TIV, A5	A5, TIV, Pt	TIV, A5	A5, TIV, Pt	TIV, A5	A5, TIV, Pt
HUMAN ACCESS (IN ADD'N TO SHUTTLE)	VEHICLE***		S		S		S
LAUNCH WINDOW	MINUTES	55	5	55	5	55	5
MMOD IMPINGEMENT	H/M/L	M	H	M	H	M	H
EARTH VIEWING	H/M/L	L	M	L	M	L	M
SOYUZ ACRV	YES/NO	Y	Y	Y	Y	Y	Y
ACRV LAUNCH VEHICLE	TYPE	SHUTTLE	SOYUZ	SHUTTLE	SOYUZ	SHUTTLE	SOYUZ
RUSSIAN ACCESS	YES/NO	NO	YES	NO	YES	NO	YES

* Solar Inertial/LVLH
** Logistics flights reduce by one flight per year when the ASRM becomes available
*** Vehicle Types are S-Soyuz, A5-Arian 5, Pt-Proton, TIV-Titan IV

Comparison of Options at 28.8 and 51.6 Degree Inclinations

The options were compared at two inclinations, 28.8 degrees and 51.6 degrees. Table 56 provides a summary comparison of key discriminating parameters for the two inclinations. The aluminum lithium external tank and advanced solid rocket motor are required for the 51.6 degrees inclination to provide adequate lift capacity for assembly and logistics. The power system performance is improved at 51.6 degree. The Option B photovoltaic modules, with both alpha and beta joints, are optimized for collection independent of inclination and therefore provide essentially the same performance in either inclination. At the 28.8 degree inclination, human access to the Space Station can only be provided by the Space Shuttle. At the 51.6 degree inclination, human access can also be provided by the Soyuz launch vehicle. Delivery of the Soyuz spacecraft to the Space Station is by Space Shuttle for the 28.8 degree inclination and by Soyuz launch vehicle for the 51.6 degree inclination. Russian access to the Space Station is limited to the 51.6 degree inclination configurations. However, Space Shuttle launch windows are significantly reduced for the 51.6 degree inclination. The micrometeorite and orbital debris level is more severe at the 51.6 degree inclination. Earth coverage for Earth viewing payloads is improved at the 51.6 degree inclination.

Comparison of Options to Space Station Freedom

Table 57 provides a summary comparison of key parameters of the options to Space Station Freedom.

While the total number of crew is identical between the options and Space Station Freedom, the requirements for maximum work hours per day and the numbers of days off are different. Space Station Freedom allows a 9.5 hour work day for a crew member with six days on and one

Table 57
Option parameter comparison with Space Station Freedom

PARAMETERS	UNITS	SSF	OPTION A1	OPTION B	OPTION C
		PMC	PHC	PHC	PHC
COST (1994-1998)	$B	15.8	13.3	13.3	11.9
SCHEDULE	MO/YR	9/00	9/00	12/01	1/01
TOTAL NUMBER OF CREW	#	4	4	4	4
TOTAL PRODUCTIVE CREW HRS/YR	HRS/YR	7680*	7680	7680	7680
TOTAL SYSTEM CREW HRS/YR	HRS/YR	1114	956	1114	814
TOTAL RESEARCH CREW HRS/YR	HRS/YR	6566	6724	6566	6866
TOTAL POWER AVAILABLE (ORB AVG)	kW	68.3	57	68.3	62.9/46.5**
USER POWER (ORB AVG)	kW	34.2	31	40.3	40.2/24.4**
MAX. 30 DAY CONT. POWER	kW	59	45.8	59	58.4/31**
POWER REGULATION	V +/- V	123+/-3	123+/-3	123+/-3	123+/-22**
TOTAL PRESSURIZED VOLUME	M^3	878	760	878	1117
NUMBER OF SYSTEM RACKS	#	65	59	65	50.5
NUMBER OF USER RACKS	#	45.5	39	45.5	72
USER RACKS @<1μg	#	29	8	29	40
OCCUPIED 30 DAY PERIODS AT LVLH	#	12	12	12	12
TOTAL LINES OF CODE	SLOCS	1685K	492K	1372K	232K
SAFE HOLD	YRS	2+	3+	2+	2
ACRV	#-TYPE	2-SOYUZ	2-SOYUZ	2-SOYUZ	2-SOYUZ
TOTAL ASSEMBLY/OUTFITTING FLIGHTS	#	20	16	20	9
TOTAL ASSEMBLY EVA	HRS	381	224	311	24
NUMBER OF LOGISTICS FLIGHTS	FLTS/YR****	4	6	6	6
MAINTENANCE EVA	HR/YR	253	187	253	80

* Freedom crew hrs have been adjusted for the same assumptions used in calculation of Option crew hrs
** Solar Inertial/LVLH
*** Power regulation to 123+/-3V provided on some channels
**** Logistics flights reduce by one flight per year when the ASRM becomes available

day off for a 90 day stay. The redesign requirements limit the crew to an eight hour work day with five days on and two days off for a 90 day stay. These requirements account for the differences in the total productive crew hours. The reductions in required system crew hours are indicative of system simplifications incorporated in the options.

Option A: This option provides a shortened core module instead of the United States Laboratory and therefore reduces the available volume. The number of payload racks within a low microgravity envelope is reduced from Space Station Freedom. The power capability is less than Space Station Freedom due to the deletion of the alpha joints which reduces array articulation capability. Assembly and maintenance extravehicular activity hours are less than Space Station Freedom due to the use of Bus-1 and simplified module and truss configurations. However, the deletion of the mobile base and the mobile transporter make the assembly task more complicated. The data management system has been simplified by deletion of the system data processors and use of a multiplex and demultiplex based system, significantly reducing the total source lines of code.

Option B: This option is similar to Space Station Freedom. A decrease in the data management system total lines of code is realized by Option B from the system modifications including deletion of a fiber distributed data interface.

Option C: This option has considerably more volume than Space Station Freedom. Power regulation is reduced. A low microgravity level is present at more payload racks than in Space Station Freedom. The single launch core design significantly reduces the number of assembly flights and the required assembly extravehicular activity. Maintenance extravehicular activity has been reduced by accommodating more subsystems within the pressurized volume. The use of the Space Shuttle type data management system has reduced the total source lines of code and additionally, significantly reduced the total number of new lines of code requiring development.

Assessment Conclusions

It is apparent from the assessment data that the Power Station and Human Tended Capability configurations do not provide adequate capability to be considered as final station configurations. In particular, these configurations preclude critical biological research which contribute to the extended human presence in space and important and evolving biotechnology research. These phases should continue to be viewed as the "stepping stones" to the final configuration. The analysis of overall capabilities should therefore be based on the Permanent Human Capability configuration for each option.

Of the hundreds of criteria considered in the assessment, there is a subset of factors which provide a determinative summary of option attributes.

The primary cost metrics are costs through 1998, costs to Permanent Human Capability and total lifecycle costs through 2010. Schedule metrics are the first element launch, initial research capability, and attainment of Permanent Human Capability.

The key metrics in enabling high priority material and life science research are mission duration as it affects available payload crew hours, payload power, payload volume and microgravity levels and durations in preferred flight modes. There is only a two percent variation in available payload crew hours between the options at Permanent Human Capability. Option A and Option C provide 10 percent less payload power than the requirement. Option C provides approximately 60 percent more volume than Option A and Option B. Microgravity levels which meet the requirements are provided at eight payload racks in Option A, 29 payload racks in Option B and 40 payload racks in Option C.

The overall accommodation of the International Partners should be viewed at a summary level as the composite of the accommodation of each individual partner. The Japanese Experiment Module, Columbus Attached Pressurized Module, and mini-payload logistics module are adequately accommodated by Options A and Option B. The Japanese Experiment Module and Attached Pressurized Module are least accommodated by Option C. The mobile servicing system is better acc mmodated by Option B than by Options A and Option C.

The major discriminating factcrs in assessing the operations characteristics of the options are assembly, ground operations and maintenance efficiencies. Option C requires approximately 50 percent fewer assembly and outfitting flights and 93 percent less assembly extravehicular activity than Option B. Option A requires approximately 10 percent fewer flights and 25 percent less assembly extravehicular activity than Option B. Ground system processing, test and verification are complicated by the number of mission build elements in Options A and Option B. The largest discriminator in maintenance is the amount of extravehicular activity required. Option C requires 70 percent less maintenance extravehicular activity than Option B. Option A requires approximately 25 percent less maintenance extravehicular activity than Option B.

The engineering characteristics of the options are not considered an overall discriminating factor. There are variations in the data management systems and electrical power systems but these are more appropriately reflected in an overall assessment as major factors that affect research resources.

Cost and schedule risk are mediated to a level basis for all options by analysis and the application of corresponding reserves. Therefore they are not overall discriminators other than how the total costs compare.

Development risk is best discrimated by the level of design maturity and degree to which proven, existing equipment is utilized. In Options A and B, design maturity is significant but the system utilized is primarily developmental. In Option C, the integrated design maturity is low but the system utilized is primarily flight proven. These counter effects result in insignificant discrimination of development risk between options.

At the Permanent Human Capability phase, there are no discriminators in safety and reliability.

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Issues

A number of issues remain to be resolved. This results from the compressed schedule to produce this report. The resolution of issues is within the current capability of the NASA and contractor team.

General Issues - All Options

1. Both the Japanese Experiment Module and the Columbus Attached Pressurized Module are heavier than the current Space Shuttle lift capability, even after removing payload and system racks from the module. Resolution is possible through upgrades to Space Shuttle lift capability, launch on Russian or Ariane launch vehicles, a combination of altitude and launch weight reserve reduction or redesign of international modules and systems. Negotiations will be required to settle this issue.

2. Orbit inclination choice is an issue. The team looked at both 28. 8 degrees and 51.6 degrees orbit inclination. The higher inclination offers dual human access (Space Shuttle and Soyuz), but requires extra up-front funding for Space Shuttle performance upgrade (aluminum lithium tank). Even then, the International laboratories are too heavy without the advanced solid rocket motor for the Space Shuttle. The advanced solid rocket motor has been delayed until December 2000, which is a significant schedule impact for the International Partners, and there are significant technical and political problems with Proton delivery of the modules. A possible solution would be a compromise orbit inclination of approximately 39 degrees achievable with the aluminum lithium tank. This allows the International modules to be launched in the Space Shuttle; and it paves the way for Proton delivery of Soyuz assured crew return vehicle, and for future delivery of Progress logistics modules. It also allows greater Earth coverage (including all the southwest United States) for assured crew return vehicle emergency landings. Dual human access would necessarily wait until approximately 2001 when Ariane and Soyuz or Ariane and European Space Agency assured crew return vehicle can be human rated. This intermediate inclination should be further analyzed before a decision on inclination is made.

3. The Space Station Freedom module design does not meet the program micrometeoroid and orbital debris requirement because the environment has changed since the design was frozen. The debris environment is predicted to be about 15 percent worse at an inclination of 51.6 degrees. The risk is in additional launch weight and cost. The Option C design incorporates the mass and cost for the upgrade contemplated in the Space Station Freedom Program. Ongoing analysis within the Space Station Freedom Program is aimed at resolving the level of protection that is required. This has not been completed and therefore the results are not available. Extra micrometeoroid shielding may have to be added to the modules in order to accommodate the latest debris model. Further analysis is required, but indications are that as much as 2600 pounds per module may be required for Options A and B.

4. Schedule and cost risk associated with renegotiating International Partner Memoranda of Understanding for changes in interfaces is a potential issue. The interface changes studied in the design options have, as yet, not been accepted by the International Partners.

   Option A and Option C have assumed that the Canadian Space Agency would provide the complete command and control system

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for the robotics, which is a change to current responsibilities. Implementation of this approach will require follow-on negotiations.

5. Reliance on the Russian space industry for Soyuz, and other Russian hardware is a risk. There are promising possibilities for cost savings with the use of Russian hardware, but there are risks associated with the stability of the Russian aerospace industry. There are also cost uncertainties associated with integration of the United States and Russian programs and hardware.

6. Both Option A and Option C, eliminate the onboard robotics maintenance depot. This will require a variation in accommodations for maintenance of the Space Station Remote Manipulator System. The flight support equipment that is necessary to launch the Canadian Special Purpose Dexterous Manipulator and Space Station Remote Manipulator System is not completely defined and analyzed in these two options. These issues are covered by allowable program adjustment funding.

7. Each option has addressed issues associated with Space Station Freedom's data management system hardware and software development and verification. The implications of the changes in the data management system are not completely understood, although all are thought to have workable solutions.

8. The Space Shuttle Program is studying the possibility of carrying two Soyuz vehicles in a single Space Shuttle flight. The issue is whether adequate clearances can be maintained between the payload elements and the orbiter, and if the overall center of gravity is within limits. The alternative is to fly two shuttle flights.

9. In Option A and Option C, the mobile transporter was deleted, and the Space Station Remote Manipulator System must move from place to place in the "inch worm" mode. The ability to assemble and maintain the station in this mode appears to be feasible, but will require further analysis.

10. The common berthing mechanism, which is used to connect nodes and modules, may have a structural problem associated with docking loads. Recent completion of analysis indicates that the docking loads cannot be reduced below 1200 pounds for the Russian docking system. The common berthing mechanism was designed for a 400 pound docking load. A common berthing mechanism modification may be required for Options A and B. This is an allowable program adjustment issue.

Option A

The following technical issues require further analysis.

1. Space Shuttle Remote Manipulator System control capability is uncertain with truss indexing operations on some flights, due to mass and center of gravity offset conditions and the mobile transporter. Preliminary analysis indicates the operations are feasible.

2. Single failure of a control moment gyro may cause the need for switch out of Bus-1. Bus-1 control moment gyros are two fault tolerant at the Permanent Human Capability configuration. However, more detailed analysis remains to be performed to fully determine that adequate attitude control margin is available at the second failure of a control moment gyro. The reliability of the control moment gyros is very high, but this will be an operational issue.

3. The trusses are packed more tightly with equipment than in the Space Station Freedom design. Initial analysis indicates the layout to be acceptable from an extravehicular activity maintenance standpoint, but may be constrained for robotics.

4. Independent analysis of maintenance and reliability indicates the number of critical orbital replacement units on the truss is still an issue for Option A-2. Extra maintenance flights may be required in order to avoid loss of a critical function during station assembly. Design iteration may also be required. Further work is required to create a higher fidelity model for this analysis for confidence in these results.

Option B

The following issues for Option B need further analysis.

1. The assembly and associated extravehicular activity hours for Option B are a significant concern. This issue is on the same order as for Space Station Freedom.

2. There was a recent independent analysis of Space Station Freedom maintenance and reliability that indicates a potential problem during assembly. Although systems have been simplified somewhat over Space Station Freedom, the number of orbital replacement units on the truss is not significantly less for Option B. Extra maintenance flights may be required in order to avoid loss of a critical function. Design iteration may also be required. Further work is required to create a higher fidelity model for this analysis for confidence in these results.

Option C

Option C has a number of issues which require further analysis.

1. The International Partners are concerned that their modules only marginally enhance the overall core station capability due to the power to volume ratio in local-vertical, local-horizontal flight mode.

   International Partners' interfaces change in the data management, power, communications and thermal control systems. International Partners roles and responsibilities must be negotiated.

2. Users are concerned about rotating acceleration vector when flying in the solar inertial mode. This issue may be mitigated through nulling the drag vector at the experiment location. This is accomplished with a sensor at the experiment location and a small thruster system. It is not yet known how large the acceptable region is, or how many experiments can be accommodated at one time. If the answer is favorable the third set of solar arrays for Option C may not be required, thus saving significant cost.

3. The developmental flight instrumentation currently installed on orbiter vehicle 102 (Columbia) is required for initial flights with the advanced solid rocket motor. Orbiter vehicle 102 is dismantled to build Option C. Instrumentation of another orbiter vehicle will be required if orbiter vehicle 102 is not rebuilt.

   In addition, the flight rate for Space Station logistics and other Space Shuttle missions will be reduced if orbiter vehicle 102 is taken out of service. The maximum flight rate will be six flights per year. Rebuild of orbiter vehicle 102 is accounted for in the costing.

4. The implications for local power regulation are not completely understood. The 120 volt bus varies from 101 to 145 volts within the core module. Optimization of regulation for equipment will be required. The number of separate power feeds in the design and operational constraints may reduce effective power to the payloads.

5. Viewing for external payloads is more difficult to accommodate because the look angle varies for celestial and Earth viewing once per orbit. Gimbals would be required for these payloads.

Further Analysis

The following items have been studied during the station redesign activity. There are no known issues according to preliminary analyses. However, further definition of the capabilities and operational concepts are required.

1. There is some concern for rendezvous and docking clearances with shortened trusses is an issue on Option A-1. If follow-up analysis deems it necessary, the module layout may have to be changed to that of Option A-2.

2. A safety analysis of returning a partially fueled Bus-1 to Earth in the Space Shuttle payload bay must be performed. Preliminary analysis indicates that, if necessary, a minor modification to the Bus-1 propellant lines will be required.

3. Fuel is transferred from the orbital maneuvering system through the Russian docking system to the Space Station propulsion system. The connections are made automatically through the docking mechanism. This system has been regularly used on the Russian Mir station, but as it is new to NASA, it will require thorough analysis.

4. The single central laboratory for Option C does not allow for crew isolation from hazardous conditions other than in assured crew return vehicles. Operational procedures will need to be developed. For significant problems the alternative is to evacuate the Space Station. Option C provides longer time for escape due to the large air volume. This is not considered to be a crew safety issue, but puts the Space Station at higher risk of abandonment in the event of a failure.

International Partners Summary

International Partners comments are summarized in the grading of the options as previously described. The United States assessment of how well the options accommodate the International Partners will be described here.

During the course of the Station Redesign activity, the International Partners were not required to negotiate possible solutions that would result in changes to their designs and therefore changes in the Space Station Freedom requirements and Memoranda of Understanding, although results of studies were provided on design changes by the European Space Agency, the Italian Space Agency and the Canadian Space Agency. Generally, the comments and grading reflect negatively on deviations from the Space Station Freedom design. However, if costs are to be reduced in the Space Station Program, then designs must be simplified and the Space Station features and interfaces will necessarily be different.

It is understandable that the International Partners would be reluctant to change designs, their program content, or interfaces when such change could result in additional cost. However, in some cases the simplifications proposed could result in reductions in cost and complexity for the International Partners.

As the United States chooses a course of action, work will be required on the part of the International Partners to contribute to the station simplification through reductions in mass and housekeeping power, and to find ways to improve interfaces.

During the Station Redesign activity, a number of areas were discussed where the International Partners could play augmented roles and could contribute significantly to the capabilities of the Space Station. Any of these ideas would require more time for technical evaluation. Examples include:

- Using the Space Station Remote Manipulator System as a nonprecision pointer for some experiments.
- Increasing reliance on a longer Italian mini-pressurized payload module was proposed in all options.
- Using international launch systems for Space Station support including launching modules, logistics or crew return vehicles.

Other areas of increased participation and utilization of international assets should be explored by all participants.

Summary

In early 1993, an Administration assessment determined that the Space Station Freedom budget ramp up in the outyears would not fit within the expected NASA budget envelope, because the new Administration wanted to increase its emphasis on other NASA programs, such as aeronautics and science. Rather than cancel the program, President Clinton directed NASA to redesign the Space Station and produce a configuration that would reduce costs, still provide meaningful international participation and provide the essential resources to advance the Nation's scientific and technology development capabilities in space.

The NASA Administrator assembled a Space Station Redesign Team in response to the President's direction. The team was to develop Space Station options that would significantly reduce development costs, while still achieving the goals for long-duration scientific research. The station Redesign Team also was charged to recommend new streamlined management structures and acquisition strategies and develop operations concepts that would cut operations costs in half. The NASA Administrator provided goals to the station Redesign Team for a revised Space Station program, as well as specific objectives and constraints in his implementation letter of March 9, 1993. The team commenced its activities on March 10, 1993.

This report describes the results of that effort. The station Redesign Team developed three design options along with a new operations concept and recommended management structures. While each option has its particular advantages and drawbacks, each option stands on its own as a technically viable Space Station that preserves international cooperation, establishes a capable space research center in orbit that will enable high priority science, technology and engineering research, and in every case do it for significantly less money than the current Space Station Freedom baseline. The options are: Option A – Modular Approach; Option B – Freedom Derived, and; Option C – Single Launch Core station.

These options:

- make varying use of Space Station Freedom systems and components, which have completed a critical design review, thus benefiting from the Nation's investment to date in the Space Station Freedom program;
- incorporate changes that would reduce complexity and increase the probability for meeting cost, schedule and mission success;
- achieve substantial savings through a streamlined management structure that provides clear lines of authority, reduces overlap and gives accountability and authority to the lowest level to get the job done, and;
- benefit from a new operations approach that would significantly reduce operations costs by consolidating similar functions at a single NASA Center, by revising the logistics approach and by accepting some risk in on-orbit efficiency.

One of the station Redesign Team's objectives was to satisfy the science and research objectives for the Space Station, and a concerted effort was made to gather requirements directly from the user communities. Materials, life sciences and engineering research were given particular attention in the design considerations as those disciplines stand to gain the most by access to a multi-purpose space laboratory. Each research requirement was reevaluated for validity to the redesign process. The critical research requirements remained the same as those defined for Space Station Freedom. Others were reduced in an effort to contain costs, but with the potential for future growth. Some requirements that had been identified previously by the research community, but not yet implemented in

the Space Station Freedom program, were reintroduced for consideration.

Another objective for the station Redesign Team was to develop options that accommodated the International Partners to the maximum extent possible. The design teams recognized that design changes in interfaces can represent costs to the International Partners and made every effort to minimize the resulting disruptions to them. As design concepts were developed, certain requirements were relaxed to obtain efficiencies and this inevitably changed interfaces and functionality between the United States and International Partner hardware elements.

Russian hardware alternatives, where they could benefit the redesigned Space Station program, were also investigated. In all three options, the Russian docking mechanism was used in the design and the Soyuz spacecraft was baselined as the assured crew return vehicle. Launch capability and other systems developed and in operation in the Russian space program are described in the report and could be considered for use in the redesigned Space Station or in future improvements.

The station Redesign Team developed an operations concept that reduces the operating costs by a factor of two from the current Space Station Freedom Program estimates. This was done while still maintaining the safety and health of the crew and the integrity of the Space Station. It has also ensured that the user community and the International Partners are provided with a capable orbiting research laboratory while balancing cost, user support capability and schedule within the constraints established. Operations cost reductions were achieved by elimination of the duplication of functions, more efficient repair and maintenance processes and risk-managed spare reductions. Significant development cost reductions were achieved by consolidation of the payload and mission operations training facilities and by a similar consolidation of control center facilities. Additionally, sustaining engineering costs will be reduced by employing a small cadre of NASA and specialized contractor personnel rather than carrying over a large staff of development contractors.

Based on the identified problems of the Space Station Freedom Program and the established selection criteria, the station Redesign Team proposes a new management organization, which includes the following attributes:

- one NASA team combining project and program levels;
- a highly effective team of demonstrated performers;
- consolidate budget authority with the Program Manager;
- consolidate and negotiate to a single prime contractor;
- utilize Integrated Product Teams, following concurrent engineering practices;
- limit the center institutional support (matrix support) to in-line tasks or facilities;
- locate the core management team in one place;
- place a skilled cadre of NASA specialists in contractor plants, and;
- combine the Space Shuttle and Space Station under a single Associate Administrator.

Depending on the configuration selected, a core office of about 250 to 300 is augmented with another 600 to 800 institutional support personnel for in-line tasks and facilities. In all cases, it is recommended that a sizable percentage of the core office, 20 to 30 percent, spend significant amounts of time in the field at the prime contractor and their subcontractors. The new program office could be located at one of a number of sites.

A dedicated transition team will be established to plan for the implementation of the redesigned Space station in terms of the redefined NASA management structure, the acquisition strategy, and the associated contract termination or descopings required by the selected redesign option.

Regardless of the redesign option selected, NASA will use a hybrid fee approach combining the features of a cost-plus-award fee contract with fee for performance incentive milestones. This fee approach provides NASA with maximum flexibility to evaluate contractor performance levels, to adjust the evaluation quickly to reflect changes in NASA management emphasis, and to focus fee on readily identifiable and measurable specific events. This will place increased emphasis on schedule, cost control and successful technical performance of the redesigned Space Station after delivery. The acquisition strategy developed for the redesigned Space Station will strengthen the integration process by removing NASA from the integrator role and selecting a single prime contractor from among the existing Space Station Freedom development contractors. This will significantly reduce the number of interfaces, complement a streamlined management structure, and make a single prime contractor accountable to NASA for the entire program.

Whichever option is chosen, the selection of the single prime should be done on a noncompetitive basis since full-and-open competition would be costly and time consuming. The prime contractor for the Space Station hardware development would be responsible for all Space Station mission and payload operations, including a sustaining engineering capability and spares for the Space Station program through completion of the development contract. Within two years prior to contract completion, a single operations contractor could be acquired on a competitive basis.

Significant streamlining in operations and management has been planned, and will be required to enable any of these options to succeed programmatically. Without the full and enthusiastic support of NASA Senior Management, it will be very difficult to effect the magnitude of change the Redesign Team is recommending. As a functioning Senior Management Team, the Center Directors and the Associate Administrators have among them the power to rationalize the roles and missions of the Centers, and to distribute the work in a way that maximizes program performance, while still satisfying geopolitical realities and constraints. This requires an atmosphere of cooperation and trust, and willingness to sacrifice for the larger good of the Agency. Care will be required to successfully make the transition from the Space Station Freedom Program to the new Space Station Program or further technical and/or funding problems will hamper its progress.

As this redesign effort was driven primarily by budget, it is important to note that while none of the three options in its final configuration meets the maximum target provided by the Administration (total of $9 billion from Fiscal Years 1994 through 1998) the three options do represent the most cost effective approaches that could be determined. Each provides at least satisfactory performance, with varying degrees of risk, schedule, and each incorporates design and operations innovations, simplification of systems, use of existing systems, and management and acquisition streamlining.

Option A and Option B would provide a limited on-orbit research capability in their early configurations within the $9 billion level, but neither option would accommodate the Japanese, European or Italian partners for that level of funding.

The Power station would allow longer Space Shuttle Spacelab flights, up to 20 days in duration. Assuming eventual stays of 30 to 45 days could be achieved, some improvement in existing material science capability could be possible, although limited power to the user (7 to 8.5 kW) would determine the size of furnaces that could be accommodated and the number of experiments that could be run simultaneously. This capability represents little improvement over current and planned Space Shuttle and Spacelab capabilities. It represents only a small return on the investment required to get to that phase, especially considering the funds already invested in Space Station Freedom to date (over $8 billion).

With additional funds, both Option A and Option B could be optimized at the human tended phase. Each option would provide a modern laboratory module and some untended research capability year round. However, at the human tended phase, Options A and B are limited by:

- a changing microgravity environment, which varies with the presence or absence of the orbiter;
- dependence on Space Shuttle stay time for experiments, which require extensive crew interaction;
- limited power, particularly when the orbiter is attached for long stays because the orbiter must draw power from the Space Station to operate its systems, and;
- an inability to achieve long-duration research goals.

As previously stated, the objective of the redesign team was to develop options for a redesigned Space Station. The team was not asked to recommend one option over the others, but rather to characterize each design's strengths and weaknesses in an unbiased manner. Each option is capable of accomplishing the mission of the Space Station. All of the options offer significant scientific and engineering research capabilities, especially in their permanently human presence stages.

NASA and its contractors can build a Space Station that fully meets the objectives of the United States and the International Partners, a Space Station that permits people to live and work safely and productively in low Earth orbit, and a Space Station that will build a bridge to tomorrow.

Appendix A - Station Redesign Team

Bryan O'Connor
Director
NASA, Headquarters

Brant Adams
NASA, Stennis Space Center

Rear Admiral Tom Betterton, USN (Ret)

Nancy Bingham
NASA, Ames Research Center

Porter Bridwell
NASA, Marshall Space Flight Center

Walt Brooks, Ph.D.
NASA, Ames Research Center

Ron Buchingham
Canada

Michele Burch
NASA, Headquarters

Fran Cannetti
NASA, Headquarters

Paolo Carosso
European Space Agency

Mary Cleave, Ph.D.
NASA, Goddard Space Flight Center

John Cole
NASA, Marshall Space Flight Center

Doug Cooke
NASA, Johnson Space Center

Jon N. Cowart
NASA, Kennedy Space Center

John Cox, Ph.D.
NASA Headquarters

Derek Deil
European Space Agency

Bonnie Dunbar, Ph.D.
NASA, Johnson Space Center

John W. Dunning, Jr. Ph.D.
NASA, Lewis Research Center

Bryan Erb
Canadian Space Agency

Melvin Ferebee
NASA, Langley Research Center

Dennis Fitzgerald
Central Intelligence Agency

Steve Francois
NASA, Kennedy Space Center

Ed Frankle
NASA, Headquarters

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National Space Development Agency of Japan

John Lawrence
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Frank Longhurst
European Space Agency

Ed Lowe
NASA Headquarters

Dick Marman
NASA, Marshall Space Flight Center

Doyle McDonald
NASA, Headquarters

Pam McInerney
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David Mobley
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General Research Corporation

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Central Intelligence Agency

Rick Nygren
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Joyce Perry
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Mal Peterson
NASA, Headquarters

James Phelps
NASA, Dryden Flight Research Facility

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NASA, Marshall Space Flight Center

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Brenda Ward, Ph.D.
NASA, Johnson Space Center

Jennifer Webb
NASA, Kennedy Space Center

Peggy Whitson, Ph.D.
NASA, Johnson Space Center

Lyn Wigbels
NASA, Headquarters

Johnson Space Center Design Support Team

Langley Research Center Design Support Team

Lewis Research Center Power Systen Design Support Team

Marshall Space Flight Center Design Support Team

*Initially chosen to lead effort, but left due to health reasons

Appendix B

National Aeronautics and
Space Administration
Office of the Administrator
Washington, DC 20546-0001

MAR 9 1993

TO: Officials-in-Charge of Headquarters Offices
Directors, NASA Field Installations
Director, Jet Propulsion Laboratory

FROM: A/Administrator

SUBJECT: Redesign Process

The President has stated his support for a strong and productive space program which includes the development of a Space Station. He wants the current Space Station redesigned as part of a program that is more efficient and effective and capable of producing greater returns on our investment. The revised station program should strive to significantly reduce development, operations, and utilization costs while achieving many of the current goals for long duration scientific research. The Redesigned program must:

1. Provide a cost effective solution to basic and applied research challenges whose merit is clearly indicated by scientific peer review, significant industrial cost sharing, or other widely accepted method;

2. Provide the capability for significant long-duration space research in materials and life sciences during this decade;

3. Bring both near-term and long-term annual funding requirements within the constraints of the budget;

4. Continue to accommodate and encourage international participation; and

5. Reduce technical and programmatic risks to acceptable levels.

<u>Constraints</u>

The Redesign Team will also be responsible for considering all phases of the program-design, assembly, operations, utilization, and management. The design of the new program will attempt to, the maximum extent feasible, use the effort expended thus far on Space Station Freedom. The design of the new program, however, shall:

1. Satisfy high priority research goals in materials and life sciences;

2. Support long-duration research (but not necessarily permanently manned);

3. Achieve initial on-orbit research capability by 1997;

4. Complete development within the 5-year budget plan,

5. Retain opportunities for international partners participation. New opportunities for Russian participation should be considered;

6. Be configured for significantly lower cost operations (in the order of a factor of two);

7. Greatly reduce on-orbit assembly and checkout;

8. Implement a simplified and effective program management structure;

9. Provide adequate budget reserves; and

10. Plan for a shorter on-orbit lifetime (e.g., 10 years extendible to 15 years).

The redesign effort will cover not only the Space Station, but will also address options for achieving earlier research results prior to Space Station availability. In particular, consideration will be given to greater use of shuttle and spacelab capabilities (which may be modified to allow longer stays in orbit) and the Russian Mir Space Station. It is important however, that we recognize our commitment to our international partners as we undertake the redesign. We must continue to accommodate and encourage international participation. Our partners will be working with us on the Redesign Team.

Objectives

The redesigned configuration will be consistent with the following objectives:

- Greatly reduce the number of shuttle launches required for deployment.

- Greatly reduce the EVA requirements during deployment.

- Greatly reduce the required number of ground operations personnel.

- Meet the minimum life science and microgravity objectives with growth potential in the out years at marginal cost.

- Advance the permanently manned capability date.

- Address technical and management issues. In particular, establish clean functional and organization interfaces to enable effective, timely decision making.
- Stimulate technology fallout.
- Reestablish national leadership in space.

Implementation

The President has directed NASA to create an independent senior-level Panel to assess the goals and redesign options developed by the Redesign Team. Details on the Panel will be available in the near future. The Panel will be required to submit its findings to NASA and report, through NASA, to the Vice-President, National Economic Council, the Office of Science and Technology Policy, and the Office of Management and Budget. An interim report will be provided by May 15, 1993, and a final report by June 1, 1993.

To assist the Panel, NASA will establish the Redesign Team. The Redesign Team will be directed by the Assistant Deputy Administrator of NASA, Joseph Shea. The team will be composed of individuals from various sectors of NASA and will also involve experts from within and outside Government and academia. The team will call upon the NASA Centers for support as required and will also involve the existing NASA and contractor Space Station organizations. The international partners will participate with the team to assure integration of their needs with each configuration.

Meaningful science and technology will be a primary consideration in assessing each configuration option. It is envisioned that the Redesign Team will provide a range of options that meet the redesign objectives, constraints, and goals. Cost and schedule data will be developed for each configuration included in the range of options to be presented by the team.

The team will plan on status reviews during the last week of each month, commencing in March, leading up to supporting the Panel interim report by May 15, 1993, and the completion of their report with appropriate recommendations by June 1, 1993. The team will consist of 30 to 35 personnel total and will be supplemented with no more than 10 individuals from the international partners.

The team will commence activities on March 10, 1993. Various alternate configurations will be studied and a baseline configuration will be maintained for each alternative. An engineering assessment will be made of the existing Space Station Freedom subsystems to determine their suitability to support the redesigned station. In addition, a review will be made to assess the cost to complete each subsystem.

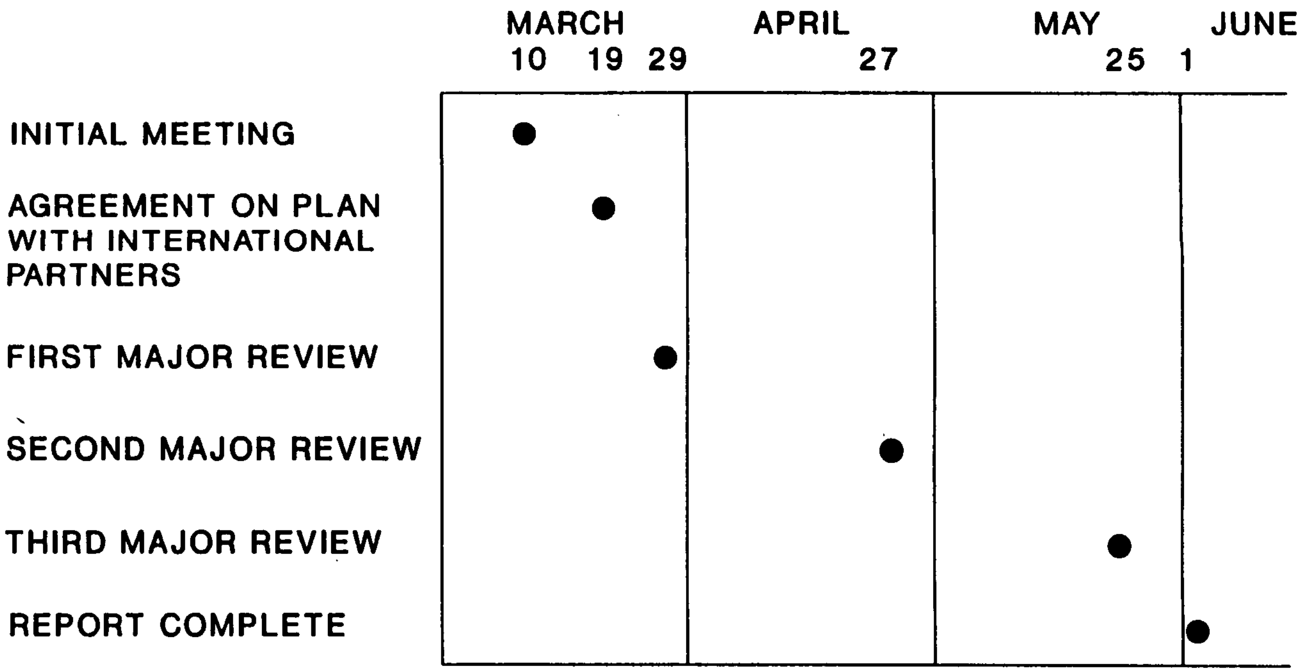
A schedule of activities is enclosed. The international partners have been provided a copy of this letter outlining the redesign process and have been requested to provide any comments by March 17, 1993. They along with other team members should plan to be in place on March 10 through the completion of the redesign effort.

Daniel S. Goldin

Enclosure

cc:
AD/Mr. Holloway
AE/Mr. Abbey
Dr. Shea

Schedule of Activities



Appendix C - Design Guidelines

Guidelines from the Administrator

All designs must:

1. Meet the budget.
2. Demonstrate adequate (up-front) schedule and budget reserves.
3. Have initial on-orbit research by 1997.
4. Complete development by 1998.
5. Have acceptable programmatic risk.
6. Have acceptable technical risk.
7. Have a 10-year on-orbit life (extendible to 15 years).
8. Include significant long-duration space research starting at Permanent Human Capability (formerly called Permanent Human Capability)
   - High priority materials science
   - High priority life science
9. Respect the commitment to the International Partners to the maximum extent possible.
10. Stimulate technical fallout.

Science, Technology and Engineering Research Design Guidelines

All designs shall:

Crew

1. Provide the minimum science and engineering research requirement of two payload dedicated crew for 90 day increments beginning with Human Tended Capability.

Power

2. Provide 30 kW power for users when the International Partners are accommodated.
3. Provide a minimum of 12 kW continuous power to an individual payload located in the minimum acceleration area (0.707×10^{-6}g for 0.01 Hz to 0.10 Hz).
4. The external attach points should be provided with not less than 3 kW total, but available to all external sites.
5. Have 28 volt DC and 120 volt AC available to paylloads: local conversion is acceptable.

Environment and Crew Health

6. Provide normoxic conditions, 21 percent oxygen, maximum 0.3 percent carbon dioxide.

External

7. Have not less than four external attach points (which includes the International Partners locations) with active cooling desirable.
8. Have a 10 megabits per second downlink capability for each external payload (may be phased).
9. Have uplink command capability for external payloads.
10. Locate external attach points for payloads in the following directions (in order of the priority):
    - Nadir (e.g., sensor development)
    - Ram/wake/port/starboard (e.g., engineering materials exposure)
    - Zenith (e.g., celestial viewing)

Data Processing

11. Have a payload data management and control computer for coordination of payload operations and data downlink. (United States Lab only)

12. The science users will provide their own experiment control and display interfaces. (United States Lab only)

Volume

13. Have no less than 35 cubic meters available to all users when the International Partners are accommodated, 13 cubic meters for payloads at Human Tended Capability (assume International Standard Payload Rack).

Microgravity Environment

14. Comply with the Space Station Freedom 1992 Program Definition and Requirements Document requirement for acceleration levels versus frequency and associated constraints.

15. Have an acceleration mapping system consistent with current Space Station Freedom baseline.

16. Have a vibroacoustic control plan which can be verified through a combination of ground modeling and testing and final on orbit verification.

Communications

17. Have a video downlink:

    - Quality of single channel downlink not less than orbiter and Spacelab

    - Video compression of at least six channels from Human Tended Capability

    - Video available during periods of untended operations.

18. Have a total downlink capability of not less than 50 megabits per second in both tended and untended operations.

19. Have an uplink video of one channel, with medium fidelity required.

20. Have total uplink of:
    - Not less than 72 kilobits per second
    - Spacelab equivalent for stored program commands and transfer to Dedicated Experiment Processors
    - Available in both tended and untended operations.

21. Have video interface and switching with not less than four payload video cassette recorders.

22. Have a data outage recorder with enough capability to capture downlink data, with loss of signal to the users of not less than Spacelab at Human Tended Capability.

Resources and Support

23. Provide a nitrogen purge supply for furnaces, combustion facilities, etc.

24. Provide potable research water.

25. Provide nonhazardous experiment gas venting.

26. Provide an optical viewing window with:
    - At least one with nadir viewing, then, in order of priority:
      - Oblique (port or starboard)
      - Zenith
      - Not less than 20 inches in diameter
      - Location optimized for uncontaminated environment
      - 0.5 kW and data available at that location

27. Provide capability to change-out payloads during the lifetime of the station.

28. Provide payload access to both air and water cooling.

29. Provide user access to the Space Station for samples, equipment, etc., with late access for launch at the launch site.

30. Provide users with logistical return of samples, equipment, etc., insuring that animals, refrigerated samples, etc., are returned to researchers in a reasonable time.

31. Have a caution and warning method for payloads adhering to a standard which shall be common among the users.

32. Provide human physiological baseline data collection capability (current orbiter and Spacelab capability is acceptable) at the landing site.

33. Include distributed science operations and training centers use distributed using commercial and NASA institutional audio, video and data communications systems.

34. Accommodate the United States position: *Integrated* payload training should be consolidated at a single location.

35. Have a logistical supply environment (for research specimens) with pressure and power and late access.

36. Utilize small, task-unique payload modules and laboratory facilities that will be flown when needed and returned to Earth when not in use.

37. Have provisions for space, power, data and other requirements (scars) available to expand subsystems in an evolutionary manner, including the capability for collecting performance data on subsystems during operations. Enough sensors should be available to provide statistically significant data.

Engineering Design Guidelines

All designs shall:

Safety Systems

1. Include station and crew survival functions which, as a minimum, are two-fault tolerant (except during assembly and maintenance).

2. Include safety monitoring, emergency controls, and mission success functions which are one-fault tolerant.

3. Have autonomous control for station critical functions.

4. Include the capability for override of all autonomous functions which will be available on board and on the ground.

5. Permit crew initiated manual overrides of time critical crew and station survival systems

6. Have emergency caution and warnings annunciated to the crew and may be on an independent path. Warning system shall alert the crew of malfunctions that threaten crew or station survival.

7. Include a fire detection and suppression capability.

8. Include an assured crew return capability at Permanent Human Capability.

9. Have a hazard analysis and containment process that adheres to *National Space Transportation System 1700.7B.*

Power System

10. Have continuous emergency power, to support station survival and crew survival functions, available in any attitude.

Data Processing Systems

11. Provide that the Data Management System transport medium be durable and easily repairable on-orbit.

12. Sensors and measurements will be consistent with the operational concept.

13. Have core system functions partitioned such that the hardware and software for station survival functions are decoupled from the hardware and software for all other station functions.

Communications Systems

14. Have communications capability to vehicles, ground and extravehicular activity.

Environmental Control And Life Support Systems

15. Maintain normoxic conditions of 21 percent oxygen and a relative humidity of 30 to 70 percent.

16. Have an environmental control and life support system sized to meet normal gas

Table 58 — Minimum Control Requirements for Failure Detection/Isolation Reconfiguration

CATEGORY	SYSTEMS FUNCTIONS	FAILURE TOLERANCE	FAILURE 1	FAILURE 2
Station Critical	DATA MANAGEMENT ATTITUDE CONTROL ELECTRICAL POWER COMMUNICATIONS	2 F.T.	AUTONOMOUS	AUTONOMOUS
Station Survival	STATION CRITICAL PLUS PROPULSION/REBOOST THERMAL CONTROL ATMOSPHERE CONTROL FIRE PROTECTION	2 F.T.	REMOTE (GROUND OR ONBOARD)	REMOTE (GROUND OR ON-BOARD)
Crew Survival	STATION SURVIVAL PLUS: CAUTION and WARNING AIR REVITALIZATION ACRV	2 F.T.	REMOTE OR MANUAL	MANUAL*
Crew Habitability	OTHER ECLSS: TEMP CONTROL WATER MANAGEMENT WASTE MANAGEMENT HUMAN SYSTEMS	1 F.T.	MANUAL*	-
Other Systems	OTHER STATION SYSTEM FUNCTIONS ABOVE MINIMUM SURVIVAL REQUIREMENTS	1 F.T.	REMOTE OR MANUAL	-
Payloads	POWER, COOLING, DATA, COMM	0 F.T.		-

*Maintenance may provide redundancy action

DEFINITIONS:

Autonomous Control	Able to do primary functions and reconfigure itself for failures
Remote Control	Accepts commands from DMS onboard or from ground
Manual Control	Manual crew input to a control device not using DMS

NOTES:

1. Categories of functions are listed from the most time critical, "Station Critical," to those which do not need immediate crew or ground response. Autonomous control will be required for functions which cannot tolerate loss of commanding.

2. In-flight maintenance may provide a level of redundancy for crew survival, habitability or other systems functions.

3. Payload support functions will generally be zero-fault tolerant, but the payloads will be required to meet "Fail-Safe" requirements.

4. This Table becomes applicable at Permanent Human Capability.

consumption and losses between logistic resupplies, plus the capability to repressurize volumes that may require it during operations and contingencies.

17. Not contribute to space debris due to their waste management system.

18. Return solid waste to Earth

19. Reprocess or safely dump liquid waste.

External

20. Keep the fluids, in the external components that handle fluids, from freezing, or design components to remain undamaged if the contained fluids are frozen.

21. Consider the preferred methods of external orbital replacement unit maintenance are, in order:
    - Robotics
    - Extravehicular activity.

22. Have a thermal control system designed to operate without planned exterior component replacement for 10 years. However, all components will be designed for repair or replacement.

Propulsion

23. Have reboost capability.

General

24. Accommodate simultaneous dual orbiter mating.

25. Have the station structure, solar arrays, radiators, attached payloads and other exterior elements allow adequate clearance for the orbiter's expected docking envelope. Other vehicles docking with the station will be expected to conform with the orbiter's envelope.

26. Have accessibility to Space Station systems performance data by onboard applications and from the ground.

27. Reach United States Permanent Human Capability by the end of calendar year 1998.

28. Have a probability of no less than .9955 of surviving a micrometeoroid or orbital debris hit during the station's ten year life

29. Maintain a capability for a two year orbit life independent of resupply.

30. Have safing features that can be selected, regardless of control failures, when using robotic devices to support extravehicular activity or other critical operations.

31. Have redundancy to protect the survival temperature of all robotic devices.

32. Include the capability that all interior compartments be able to be individually depressurized and repressurized by local control, from another compartment or from the ground, as required.

33. Isolate all pressurized compartments when the crew leaves the station.

34. Perform only operations that have adequate hazard detection and control in untended mode.

Special Note

All references to Space Station Freedom components (weight, power, volume, maintenance crew time, thermal and logistics) shall be directly traceable to the March 1993 submissions (by the Work Packages and International Partners) of the above data to Space Station Freedom Level II Resource Margin Summary. All designs shall:

Operations Design Guidelines

Safety

1. Have fail safe payload support systems.

2. Define the maximum altitude allowed by the radiation exposure limits of the crew when a crew is present.

3. Have a safe haven capability.

4. Have consumables and system capacities with sufficient margin to continue operations and endure a missed logistics resupply cycle without endangering the crew or station.

Crew

5. Have a minimum crew size of three when the station is operational.

Data Processing

6. Display station and payload health, status and safety data on-orbit.

General

7. Include an integrated logistics support concept.

8. Include an assembly plan.

9. Include a test and verification plan.

10. Utilize standardized tools and equipment necessary to analyze problems and to repair and modify process hardware which will be available for internal payload experiments.

11. Provide for safe disposal of the station at the end of its useful lifetime.

12. Include an airlock.

13. Provide for a mission director and a station commander.

    - The mission director will be established on the ground and be responsible for:
      - Execution of mission objectives
      - Mission planning
      - Tasking
      - Allocation of priorities, resources
      - Flight planning
      - Resupply, rendezvous planning
      - Contingency operations
    - The Station Commander will direct on-orbit activities, and will be responsible for:
      - Health and safety of the crew
      - Integrity of the station
      - Accomplishment of the missions and tasks assigned.

Guidelines Derived From The Existing International Agreements

The below listed guidelines include those developed and agreed by the four Partners, as derived from the top-level commitments undertaken by these Partners in the Intergovernamental Agreements and the Memoranda of Understanding. For completeness, certain agreements derived from the Memorandum of Understanding with the Italian Space Agency have also been incorporated. These guidelines, together with those developed in the United States, will constitute the total set of guidelines to be used in the initial definition of redesign options and the assessment of options throughout the redesign effort.

1. The technical and programmatic baseline of any option shall include the assembly of the Attached Pressurized Module, Japanese Experiment Module, Mobile Servicing System, and the Mini-Pressurized Logistics Module as well as the necessary resources to support their operations and utilization (i.e., The Attached Pressurized Module, Japanese Experiment Module, or Mobile Servicing System should not be associated with a growth configuration or planning).

2. The technical and programmatic baseline shall achieve Fermanent Human Capability (formerly called Permanent Human Capability) on a timeline agreed by all Partners.

3. The schedule for the Mini-Pressurized Logistics Module development and the Attached Pressurized Module, Japanese Experiment Module, and Mobile Servicing System launch and outfitting shall not significantly deviate from current Space Station Freedom baseline.

4. A crew of four shall remain the minimum at Permanent Human Capability.

5. A growth potential for a crew of eight and 75 kW power shall be maintained.

6. The "new" on-orbit operational life requirement shall be counted from the time of completion of assembly, including the Attached Pressurized Module, Japanese Experiment Module and Mobile Servicing System. On-orbit operational lifetime shall be coordinated among the Partners.

7. The Space Station Freedom system requirements applicable to the Attached Pressurized Module, Japanese Experiment Module, Mobile Servicing System (through the Program Defintion and Requirements Document and Joint Program Definition and Requirements Document), and the Mini-Pressurized Logistics Module shall be kept to the maximum extent. Impact of deviations to be assessed and agreed by the management mechanisms provided by the Memoranda of Understanding.

8. Same for any already established technical interfaces and interface control documents between Space Station Freedom, the Attached Pressurized Module, Japanese Experiment Module, Mobile Servicing System, and the Mini-Pressurized Logistics Module ***and*** to payloads.

9. Shuttle launch performances and interface requirements for the Attached Pressurized Module, Japanese Experiment Module, Mobile Servicing System and the Mini-Pressurized Logistics Module shall not be modified.

10. In assessing the operations scenario and costs, proposed additional contributions from the International Partners and Italian Space Agency's willingness to consider elevating the priority of the Minilab shall be taken into consideration.

11. The Mini-Pressurized Logistics Module shall be considered the pressurized carrier to support initial on-orbit research capability. Significant use of the Mini-Pressurized Logistics Module is to be envisaged once the development of the Space Station is complete.

12. The NASA and Italian Space Agency agreement that a joint decision will be made in December 1994 on the Italian Space Agency's provision of a Minilab shall be considered in the assessment of each option.

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Appendix D - Subsystems

Subsystem: Data Management System

Function	Option A	Option B	Option C
Distributed data interface	1553-1Mbps	FDDI - 10 Mbps (3)	1553-1Mbps
Processors	MDM	SDP	GPC (2)
Memory	3 Mbytes	16 Mbytes	256 kbytes
CPU	1.6 mips	3.9 mips	1.2 mips
Mass storage	40 Mbytes	320 Mbytes	16 Mbytes
Workstation	Laptops	MPAC	DDU & keyboard
Memory	200 Mbytes	16 Mbytes	2.5 Mbytes
CPU	20 mips	3.9 mips	2.6 mips
International gateway	yes (1)	yes	yes (1)
Payload processor	MDM	SDP	GPC (2)
Local bus	1553	1553	1553/RS-422
Lines of code (PHC)	492k	1372k	232k

(1) Does not allow a 802.4 international interface but provides a 1553 interface
(2) Orbiter computer
(3) Separate Fiber Distributed Data Interface (FDDI) for payloads deleted

MDM: multiplexer/demultiplexer
SDP: standard data processor
GPC: general purpose computer (Shuttle)
mips: million instructions per minute
MPAC: multi-purpose access computer
DDU: digital display unit

Subsystem: Structures and Mechanics

Function	Option A	Option B	Option C
Airlock	yes	yes	not required
CETA device	yes	yes	not required
CBM	yes	yes	yes
Cupola	yes	yes	no (1)
Mobile transporter	no	yes	not required

(1) Utilizes the 6 windows

CETA: crew equipment translation aid
CBM: common berthing mechanism

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Subsystem: Electrical Power System

Function	Option A	Option B	Option C
Solar arrays	2 - Power Station 6 - PHC	2 - Power Station 6 - PHC	N/A 4 - PHC
Alpha gimbal	no	yes	no
Beta gimbal	yes	yes	no
Output per array/wing			
51.6 degrees	12.3 kW	12.7 kW	15.3 kW (SI) 11.8 kW (LVLH)
28.8 degrees	11.6 kW	11.8 kW	14.4 kW (SI) 8.5 kW (LVLH)
Output per channel			
51.6 degrees	6.1 kW	12.7 kW	5.1 kW (SI) 3.9 kW (LVLH)
28.8 degrees	5.8 kW	11.8 kW	4.8 kW (SI) 2.8 kW (LVLH)
Fault tolerance	2 @ 1st flight	1 @ 1st flight	2 @ 1st flight
Regulation	yes	yes	no (1)
Parallel bus	yes	yes	no
Auto/manual distribution	auto	auto	manual (2)
voltages	113-120 vdc	113-120 vdc	105-140 vdc; 19-32 vdc

(1) Regulated voltage provided to International Partners
(2) Auto for critical systems only

SI: solar inertial attitude
LVLH: local-vertical local-horizontal attitude

Subsystem: Guidance, Navigation and Control System

Function	Option A	Option B	Option C
Propellant	Bi-propellant MMH/N_2O_4	mono-propellant hydrazine	Bi-propellant (1) MMH/N_2O_4
Motors			
Boost	2 @ 110-300 lbs/ea	3@ 20-55 lbs/ea	6 @ 870 lbs/ea (2)
Attitude control	12 @ 10-22 lbs/ea	10 @ 9-25 lbs/ea	12 @ 25 lbs/ea
Number of CMGs	6	4	4
Momentum capability (ea)	1700 ft-lbs-sec	3500 ft-lbs-sec	3500 ft-lbs-sec
Star trackers	yes - 3	yes - 2	no
Global Positioning System	yes	no	yes
Passive dampers	no	yes - 4	not required

(1) Orbiter propellant
(2) Orbiter Reaction Control System and vernier thrusters

MMH/N_2O_4: monomethylhydrazine/nitrogen tetroxide
CMGs: control moment gyroscopes

Subsystem: Thermal Control System

Function		Option A	Option B	Option C
Cooling fluid	PVTCS:	1 phase ammonia	1 phase ammonia	(1)
	ETCS:	1 phase ammonia	2 phase ammonia	1 phase freon
	ITCS:	1 phase H_2O	1 phase H_2O	1 phase H_2O
Loops and temperature				
Power module		2 PV1 & 1 PV2	2 PV1 and 1 PV2	(1)
ETCS loops		1 low & 1 medium	1 low & 1 medium	4 low
ITCS loops		1 low & 1 medium	3 low & 3 medium	2 low/medium
Rejection capability				
Power module		11.3 kW	16.7 kW	(1)
ETCS loops		68.0 kW	95.0 kW	54.0 kW
Power required				
Power module		1.076 kW	.794 kW	(1)
ETCS loops		1.060 kW	.691 kW	1.702 kW
ITCS loops		1.100 kW	1.494 kW	.997 kW
Weight				
Power module		8,229 lbs	7,228 lbs	(1)
ETCS loop		19,624 lbs	18,021 lbs	22,540 lbs
ITCS loop		3,582 lbs	7,799 lbs	3,791 lbs

(1) PVTCS and ETCS combined

PVTCS: photovoltaic thermal control system
ETCS: external thermal control system
ITCS: internal thermal control system
PV1 and PV2: photovoltaic arrays 1 and 2

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Appendix E - Alternative Transporation Options

This appendix contains a discussion of the vehicles, capabilities and comparisons made as part of the Alternative Transportation Options assessment performed by the Station Redesign Team. Since the expendable launch vehicles of the United States and the International Partner countries are relatively well known, general descriptive information of these vehicles has not been included. However, because of the recent exchanges with the Russians, new information regarding their expendable launch vehicles and space vehicles has become available. Therefore, some detail on these systems is presented in this appendix.

Russian Expendable Launch and Space Vehicles

Several Russian space transportation systems in operation today could be applied to Space Station assembly, logistics and human transportation.

Expendable Launch Vehicles

The following vehicles would launch from the Baikonur Cosmodrome in Kazakhstan (latitude of 45.6 degrees North).

Soyuz: The Soyuz launch vehicle has flown over 1400 times since 1957. It is a two and one-half stage vehicle; all stages use liquid oxygen and kerosene as propellants. None of the stages is known to have throttling or restart capability. The core first stage and four strap-on boosters are ignited at lift-off. When all propellant in the boosters has been consumed, they are jettisoned; the core continues to burn until its propellant supply is exhausted, at which time it is jettisoned and stage 2 is ignited. Stage 2 provides final orbit insertion (typically of a Soyuz TM or Progress spacecraft).

The Soyuz launch vehicle has direct applications for launch of crewed Soyuz TM, Soyuz assured crew return vehicle or Progress resupply vehicles to a Space Station at 51.6 degree inclination. As the Soyuz and Progress spacecraft are sized for this vehicle and given the range safety constraints, there is no capability for delivery to orbit inclinations lower than 51.6 degrees. Detailed information regarding the Soyuz launch vehicle has not been pursued with the Russian delegation.

Proton: The Proton has been the primary heavy lift launch vehicle since the late 1960s. It is the only Russian vehicle capable of placing payloads into geostationary orbit. A three stage and a four stage version of the Proton exists. Stage 1 consists of six strap-on fuel tanks attached to a single shared core oxidizer tank; each fuel tank has its own engine. Upon shutdown, the core tank and strap-on fuel tanks are jettisoned as a single unit. The four stage 2 engines then ignite; when stage 2 propellant is exhausted, it is jettisoned. Stage 3 has a single main engine; for a three stage mission, stage 3 places the payload into low Earth orbit; for a four stage mission, stage three is typically jettisoned just prior to reaching orbit. The first three stages all employ nitrogen tetroxide and unsymmetrical dimethyl-hydrazine as propellants and are neither throttleable nor restartable. For the four stage vehicle, stage 4 places the payload into a low Earth parking orbit and then executes the proper series of burns to fulfill the mission requirements. Stage 4 burns liquid oxygen and kerosene, and may be restarted up to seven times. However, it does not possess throttling capability.

The Proton is a proven vehicle with cargo lift capability to 51.6 degree inclination that is comparable to, or greater than, any other operational expendable launch vehicle. It has been used routinely for delivery of Salyut and Mir space stations modules. An estimated 209 launches of the Proton family (including an early two-stage version) have been attempted since 1965, including an estimated 26 three-stage Proton and 179 four-stage Proton vehicles. Historical reliability of the Proton, during a span of 107 launches between

1983 and 1992, is 94.4 percent. For 37 launches during the 1989 through 1992 timespan, reliability was 97.3 percent. Proton is launched into initial orbit inclinations of 51.6 degrees, 65 degrees and 72 degrees, which are limited by downrange stage impact zone and overflight constraints. The fourth stage, referred to as the Block DM, is used for subsequent payload transfer to high altitude and/or low inclination orbits, typically for geosynchronous missions, or transfer to interplanetary orbits.

The three-stage Proton could deliver Space Station assembly elements or large logistics payloads to an inclination of 51.6 degrees. Payload mass delivery capability to a 108 nautical mile altitude circular orbit is reported to be approximately 46,300 pounds. In combination with an orbital transfer and rendezvous and docking stage, large payloads could be delivered directly to the Space Station. A modernized Proton is currently in development and is planned to be available by 1995. Several vehicle systems will be upgraded; three-stage performance capability is planned to improve to approximately 48,500 pounds to the 108 nautical mile circular orbit.

Existing versions of Proton fairings (having a maximum external diameter of 13.45 feet) are not adequate for large diameter cargoes. Salyut and Mir modules have been flown with partial payload fairings covering sections of the modules. A new fairing would need to be developed to accommodate Space Station modules.

The inclination capability of the existing four-stage Proton is dependent on spacecraft configuration and weight. Approximate capabilities are summarized in Table 59. The table includes data provided by NPO Energia and data generated through NASA independent simulation. Further detailed analysis would be required to resolve any differences. NPO Energia data for the modernized Proton were generated using a nonstandard ascent profile which assumes large suborbital burns of the fourth stage. Range safety constraints may not have been applied.

Table 59
Proton inclination capability for selected missions

		Minimum Orbit Inclination Capability			
	Spacecraft	**Existing Proton**		**Modernized Proton**	
Mission	**Weight**	**NASA***	**NPO-E**	**NASA***	**NPO-E**
Soyuz TM	15,587 lbs.	-	-	-	36°
- crew of 3					
- escape system					
Soyuz ACRV					
- max. projected weight	16,300 lbs.	36°	34.6°	34°	31.5°
- min. potential weight	15,200 lbs.	34.5°	33.2°	33°	30.1°
Progress M	16,138 lbs.	36°	34.4°	34°	31.2°

* Minimum inclination limits are necessarily imprecise due to limited detailed knowledge of Russian systems.

The existing four-stage Proton and the planned modernized Proton do not have sufficient performance capability to deliver a standard Soyuz TM or Progress M spacecraft to an inclination of 28.8 degrees. It is not clear that the Proton could be further upgraded to achieve that objective without the addition of a new liquid oxygen/liquid hydrogen upper stage. Human-rating of the Proton would be required to support crewed Soyuz TM missions.

Zenit: The Zenit is a two-stage launch vehicle. All launches currently take place from the Baikonur Cosmodrome; a launch site at Plesetsk is in work but has been delayed. Stage 1 employs a single engine with four combustion chambers; this engine is throttleable. Upon stage 1 shutdown, stage 2 ignites and places the payload into low Earth orbit. The single stage 2 main engine is also throttleable; neither engine is capable of restart.

The Zenit has been launched 20 times since its introduction by NPO Yuzhnoye, of the Ukraine, in 1985. Three consecutive failures between 1990 and 1992 have been followed by three consecutive successes since November 1992. The Zenit is limited to near 51.6° for Space Station applications because of its performance capability and stage impact zones. Zenit performance is shown in Table 60. Zenit offers a capability which is well-matched with Progress-derivative logistics vehicles. A Progress MT resupply vehicle, described in the following section, launched on a Zenit would deliver up to approximately 13,000 pounds usable cargo to the Space Station. Existing fairings are adequate to support Progress-type missions. The Zenit was designed as a potential Soyuz launch vehicle replacement for Soyuz TM spacecraft launches and is thereby human-ratable. This operational mode will not be further considered until Zenit reliability is proven through additional flight experience.

Space Vehicles

Progress Resupply Vehicle: Versions of the Progress resupply vehicle have supported the Salyut and Mir space stations since 1978. The Progress M spacecraft is the second generation of Progress, incorporating system changes made during the Soyuz upgrade to the TM version. The Russian delegation provided detailed data regarding three versions of the Progress spacecraft which could be applied to the Space Station: the existing Progress M and two proposed modifications. Illustrations of these spacecraft are included in Figure 116.

The existing Progress M is specifically suited to the logistics requirements of Mir; it has a pressurized cargo compartment and a refueling module, from which Mir propellants, water and oxygen are replenished by transfer through ducts to the Space Station. The pressurized cargo capability is approximately 4,000 pounds, within a volume of 247 cubic feet. The total cargo capability, including liquid and gas consumables, is approximately 5,500 pounds when launched on the Soyuz launch vehicle. The Progress M autonomously rendezvous and docks with Mir, with a real-time data link to the ground controllers and Mir crew. Pressurized cargo is transferred manually by the Mir crew and is limited in size by the 2.62 feet diameter Progress and Mir hatches. This spacecraft could be launched on a variety of international launch vehicles, such as Atlas, Titan, Ariane or the H-II. The spacecraft launch mass is approximately 16,100 pounds.

The Russian delegation proposed a modified version of the Progress M, replacing the existing cargo and refueling modules with a larger pressurized cargo module, to better suit the redesigned Space Station logistics scenarios. The launch mass of 16,100 pounds was retained to allow continued use of the Soyuz launch vehicle; the pressurized cargo capability was increased to approximately 7,000 pounds within a volume of 459 cubic feet, retaining the existing 7.2 feet cargo module external diameter. The hatch diameter of 2.62 feet would likely be retained because of this vehicle diameter. The modified Progress M could be launched on a variety of international vehicles. To take advantage of the increased lift capability of some of these other launch vehicles, it would be beneficial to increase the pressurized cargo load of Progress M.

The Progress MT service module, containing the propulsion, power, control systems, etc., is an upgrade from the standard Progress M service module. The Progress MT concept illustrates that a Progress-derived logistics vehicle could be sized optimally for any selected international launch vehicle. The Progress service module, in conjunction with a payload-attached forward rendezvous and docking electronics system and docking mechanism, could serve as a transfer vehicle for a variety of Space Station payloads.

Table 60
Reported Zenit performance capability summary

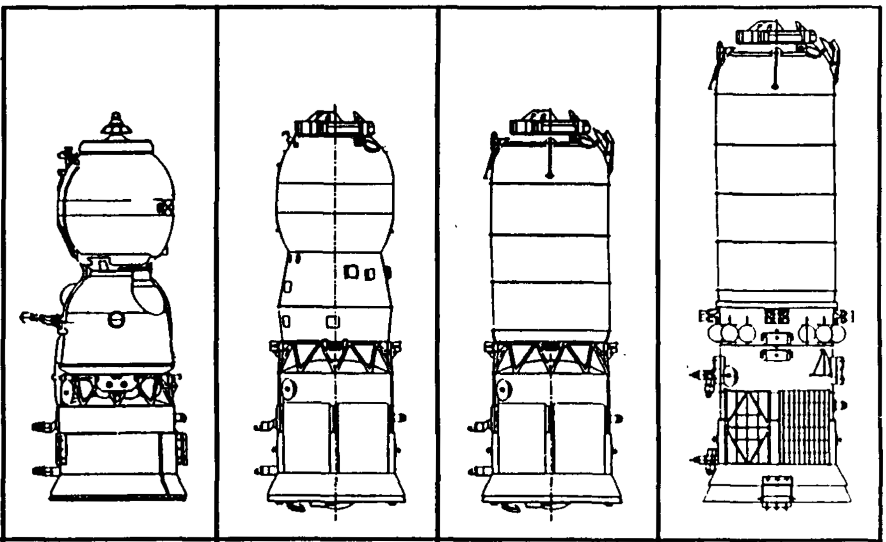
Launch Vehicle	Orbit Site	Orbit Altitude	Payload Inclination	Weight
Two-stage Zenit - circularization with 2nd stage steering engines	Baikonur	216 nm	51.6°	25,600 lbs.
	Plesetsk	216 nm	63.4°	24,900 lbs.
Three-stage Zenit - Block DM 3rd stage	Plesetsk	216 nm	28.5°	2200-4400 lbs.

A Progress MT vehicle concept has been defined for use with the Zenit launch vehicle. This spacecraft has been considered for use with the Mir program, so it has liquid and gas storage and refueling capability similar to the standard Progress M. The projected pressurized cargo capability is approximately 13,000 pounds within a 663 cubic foot volume with a cargo module external diameter of 7.2 feet. With a diameter increase to 10.2 feet, the cargo volume grows to approximately 1060 cubic feet (cargo weight capability stays at 13,000 pounds as it is limited by Zenit lift capability). It is possible that the 10.2 feet diameter version could accommodate a hatch with a diameter larger than 2.62 feet.

FGB Universal Salyut Block: The FGB Universal Salyut Block is a complex spacecraft system containing propulsion, power, guidance, navigation, control, thermal, communications and life support systems. It is capable of flying as a human-rated free flyer. Various downsized versions of this full-capability system have been integrated into prior Mir module and Kosmos missions to provide payload support functions, propellant transfer, rendezvous and docking operations. This vehicle has an internal propellant capacity up to 21,160 pounds, with the ability to carry additional propellants external to the basic structure. It has flown with 20 kW of power, with capability of approximately 30 kW. It can stabilize and control up to 275,000 pounds. Versions of this stage have been flown on numerous Kosmos, Salyut spacecraft and the Kvant and Kristall modules currently on the Mir space station complex. The use on Kvant is illustrated in Figure 117. It will also be used on the Priroda and Spectr modules, planned for delivery to Mir within the next two years. On the Kvant module, the stage was separated from the module after delivery to Mir. For the other Mir modules, the stage remains integrated to the attached modules.

Salyut Space Tug: The Salyut space tug, a downsized version of the FGB, is 13.45 feet diameter by 11.5 feet long; dry mass is 5500 pounds, with a propellant load of 2760 pounds. This propellant load is sized for planar orbital transfer operations. It cannot accomplish significant orbit inclination changes for payloads in the assembly module class. The performance of larger propellant load versions of this stage is evaluated in the following section.

C-4



Vehicle	Soyuz TM	Progress M	Modified Progress M	Progress MT
Weight Height Maximum diameter	15,600 lb 22.9 ft 8.9 ft	16,100 lb 24.4 ft 8.9 ft	16,100 lb 24.4 ft 8.9 ft	28,100 lb 30 ft 8.9 - 10.2 ft
Pressurized cargo volume	N/A	247 cu ft	459 cu ft	663 - 1060 cu ft
Cargo capacity within pressurized volume	N/A	4000 lb	7000 lb	up to 13,000 lb

Figure 116
Soyuz and progress vehicle concepts

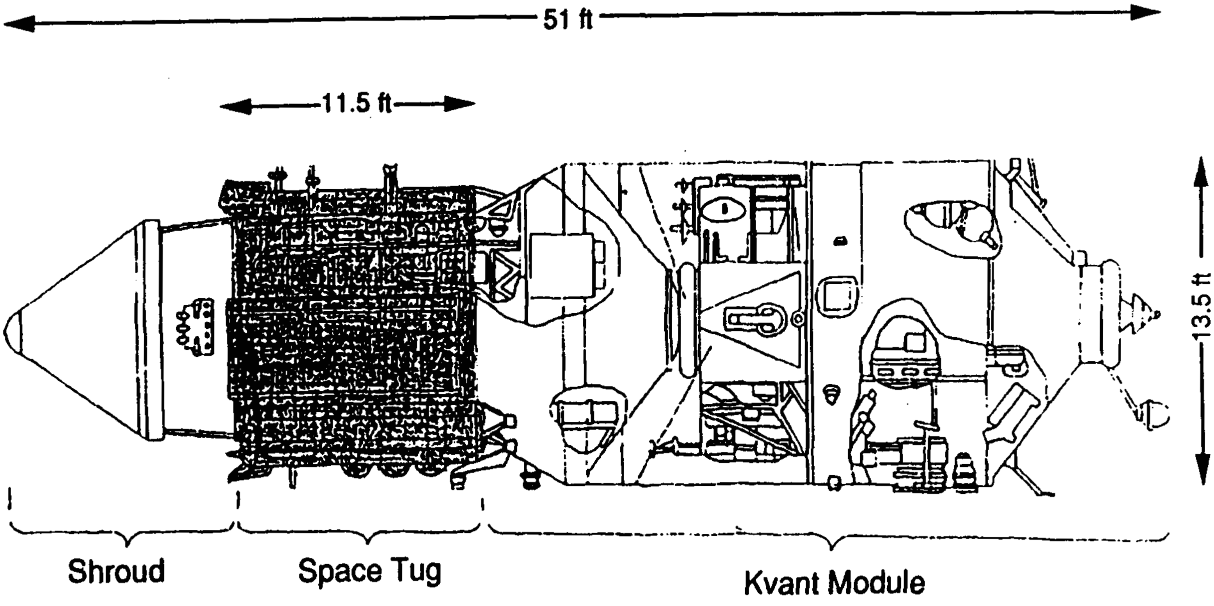


Figure 117
Use of FGB Universal Salyut block for delivery of Kvant module

Supporting Analysis

Launch Azimuth Constraints

Evaluations focused on use of the Baikonur Cosmodrome which is located at an approximate latitude of 45.6 degrees North. The lowest orbit inclination that can be reached from Baikonur, through a launch at a due east azimuth of 90 degrees (measured clockwise from north) without the use of ascent or orbital maneuvers designed to change the orbit plane, is therefore 45.6 degrees. Launch vehicle performance would be at its maximum at this launch azimuth and resulting orbit inclination. Range safety considerations, however, constrain Baikonur launches to more northerly azimuths (except for some particular cases such as for polar orbits). Because of a significant amount of Russian and Chinese land overflight, Russian expendable launch vehicles are restricted to specific launch azimuths to minimize land impact of spent stages and jettisoned hardware (planned or accidental) on or near populated regions. The ascent trajectories have been designed to drop spent stages and other jettisoned components (e.g., payload fairings) in designated zones within the boundaries of Russia or Kazakhstan, and to minimize, to the extent practical, the overflight of other countries.

Figure 118 illustrates these constraints for the case of the Proton launch vehicle. Hardware impact zones and instantaneous impact points are plotted for three inclination cases, the theoretical performance optimum of 45.6 degrees, the standard Proton launch inclination of 51.6 degrees, and an alternate Proton inclination of 65 degrees. The instantaneous impact point trace represents the possible locations of launch vehicle impact due to instantaneous loss of thrust throughout the ascent trajectory. It can be seen in the figure that the 51.6 degree trajectory provides for programmed hardware impact in Russia and Kazakhstan, with overflight of a small section of northeast China. This results in a significantly reduced probability of hardware impact in Chinese territory, as compared to the due east launch case illustrated in more detail in Figure 119. A due east launch to a 45.6 degree inclination would result in an instantaneous impact point dwell time over China of more than four minutes, and impact points passing through major population areas. A future launch at 45.6 degrees is highly unlikely due to safety and political considerations.

United States and International Partner launch vehicles are relatively less constrained by launch site latitude and hardware impact considerations. Stage and hardware disposal is designed to occur in ocean areas and need only avoid islands and land mass coastlines. The highest inclination that can be achieved by United States vehicles without ascent steering is approximately 57 degrees to avoid the United States land mass.

Human Access Analysis

Today, the only operational human-rated space transportation systems are the United States Space Shuttle and the Russian Soyuz TM delivered to orbit by the Soyuz launch vehicle. The Space Shuttle has the capability to deliver humans and cargo to the entire range of inclinations considered. The Soyuz launch vehicle, having been designed for optimal delivery to the Soviet Space Stations (Salyut and Mir), has maximum capability to an orbital inclination of 51.6 degrees. The primary mission of the Soyuz TM is delivery and return of humans. Minimal cargo is carried on the Soyuz TM vehicle. Cargo is instead delivered independently by the Progress M vehicle launched atop the Soyuz launch vehicle.

To increase the inclination range to which the Soyuz TM may be delivered, it could conceptually be launched by more capable booster vehicles. Being a Russian asset, minimal integration issues would be faced if it were launched by another of the more capable Russian boosters (i.e., Proton or Zenit). However, it could as well be delivered by the European Ariane IV or Ariane V, the Japanese H-II, or United States Atlas or Titan class launch vehicle. The inclination range to which the Soyuz could be delivered is dependent on the launch site and launch vehicle capability.

The Ariane V and Zenit are planned to be human-rated. Ariane human-rating is achieved by a parts reliability program and redundancy considerations within the basic design together with a rigorous test and verification program that will include instrumented test flights and a series of flights with unmanned payloads. The Zenit human-rating potential is discussed in the Russian Expendable Launch and Space Vehicles

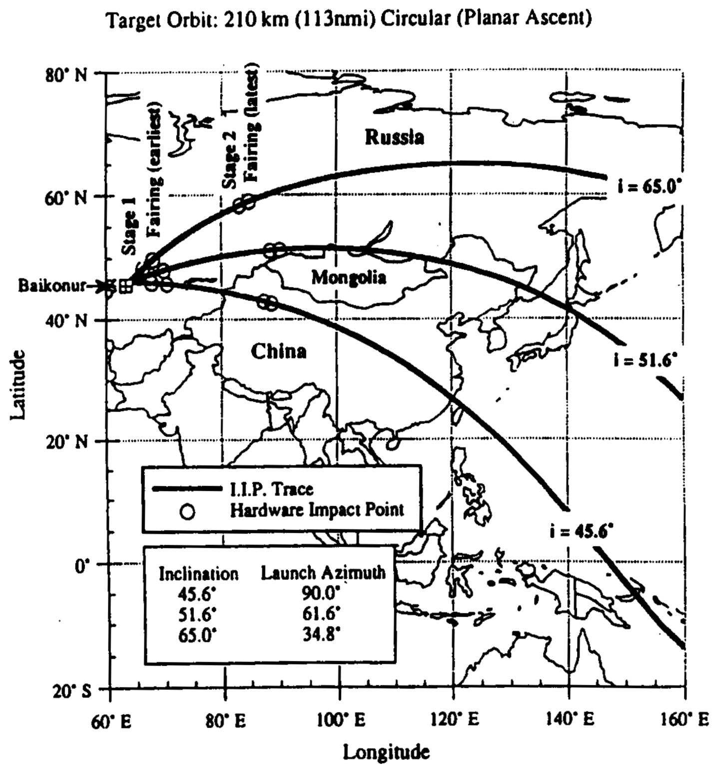


Figure 118
Vacuum instantaneous impact point traces and hardware impact points for Proton

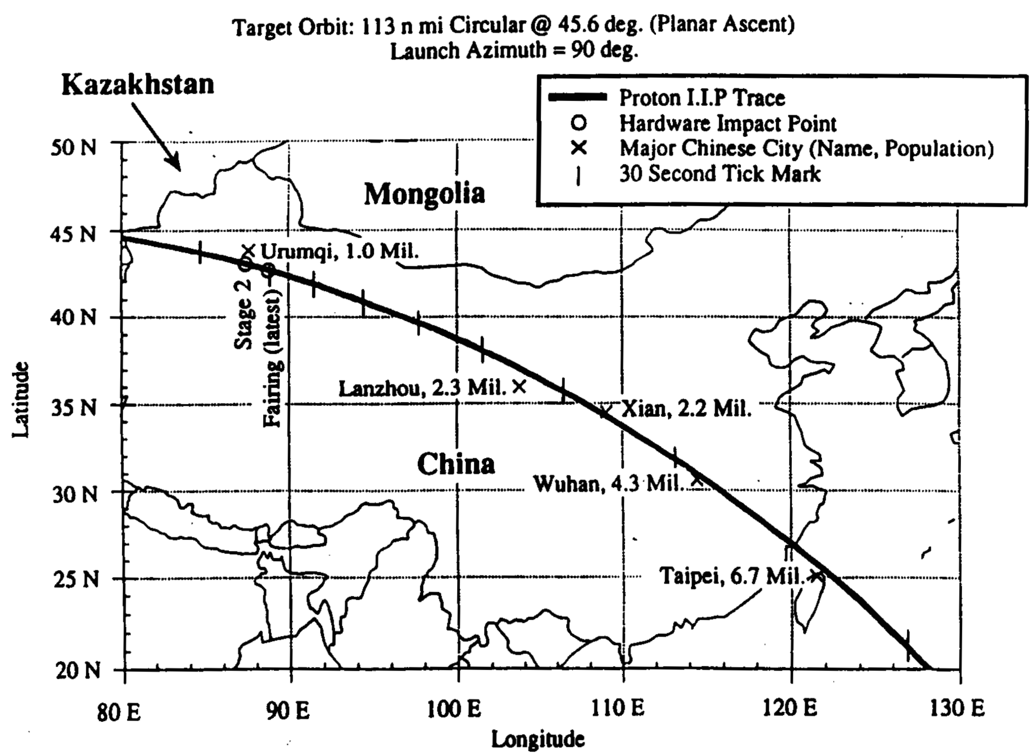


Figure 119
Vacuum instantaneous impact point traces and hardware impact points for Proton due east launch from Baikonur

Table 61
Options for human access to Space Station applicable inclination ranges

Vehicle	Inclination Range	Human-Rated
Space Shuttle	28.8° - 51.6°	Yes
Soyuz TM/Soyuz Launch Vehicle	51.6° only	Yes
Soyuz TM/Ariane 5	28.8° - 51.6°	Designed to be
Soyuz TM/Proton	36° - 51.6°	No
Soyuz TM/Zenit	45° * - 51.6°	Designed to be
Soyuz TM/H-II	28.8° - 51.6°	No
Soyuz TM/U.S. ELV	28.8° - 51.6°	No

* Liens on booster performance due to escape system will determine lower inclination limit

section of this appendix. Neither the Ariane IV nor the H-II are intended to be human-rated.

Table 61 shows the human access options and the applicable inclination ranges.

Cargo Access - Assembly and Logistics Analysis

The options for delivery of cargo, either for assembly or logistics, are much greater than for delivery of humans simply due to the number of available expendable launch vehicles. One of the largest issues associated with delivery of cargo or assembly elements is the necessity of providing a transfer stage to maneuver payloads from a phasing orbit to the Space Station. The United States does not possess such a vehicle. However, Russia has employed autonomous rendezvous and docking for more than 15 years with its Salyut and Mir space stations. This has been accomplished via the Progress series of resupply craft and the FGB Universal Salyut Block integrated with Mir modules.

Because of their limited cargo capacity, the Progress M and its variants would be used for delivery of smaller logistics elements. The recently proposed Salyut space tug could be used for the autonomous delivery of assembly elements. Although not equipped with autonomous rendezvous and docking hardware itself, this stage has performed as part of autonomous rendezvous and docking systems in the past (e.g., delivery of Mir-1 modules). The Progress series could also be integrated with a variety of international launch vehicles including the Russian boosters, thus providing a spectrum of capabilities from different launch sites around the world. Finally, using only the propulsion module and necessary autonomous rendezvous and docking avionics from the Progress, a Progress Derived Transfer Stage could be built to deliver a Space Station assembly or logistics element.

The only other potential transfer vehicle currently planned is the European automated transfer vehicle. Projected availability of this vehicle is in the year 2000. The automated transfer vehicle would be capable of delivering cargo and large Space Station elements (e.g., international pressurized modules). The usable cargo and carrier weight delivered to the Space Station, as a function of inclination for a variety of existing and potential vehicle configurations, is shown in Table 62. For the Space Shuttle, usable cargo and carrier weight is defined as the difference between the Space Shuttle gross lift capability and the launch package integrator weight. For assembly and logistics missions the launch package integrator weights are 6,000 pounds and 7,200 pounds, respectively. All Space Shuttle capability figures have assumed a Space Shuttle program manager's reserve of 3,500 pounds. Table 63 shows general Space Shuttle capabilities for different Space Shuttle configurations at 28.8 degrees and 51.6 degrees with three different launch package integrator weights. The first two flights of the advanced solid rocket motors will be test flights, with an assumed performance gain of 8,000 pounds over the baseline Space Shuttle, and were not considered in this analysis. Flights 3 through 10 will assume a gain of 10,000 pounds. Flights 11 and subsequent will gain 12,000 pounds.

For expendable launch vehicles with transfer stages, usable cargo and carrier weight is defined as the difference between the expendable launch vehicle gross lift capability to the Space Station orbit and any integration hardware weight necessary to launch the cargo and its carrier. For the Progress vehicles, the weight shown is the delivered cargo weight since the Progress vehicles proposed by the Russian delegation include a pressurized carrier.

As can be seen from Table 62, many of the capabilities are the same at both inclination limits. This is because the Progress carriers, as proposed by the Russian delegation, have not necessarily been optimized for the various launch vehicles. Thus, payload capability is limited by the volume of the carrier rather than the capability of the launch vehicle. Optimized Progress carrier sizing would result in greater capability at 28.8 degrees and 51.6 degrees for Atlas, Titan, Ariane and H-II. Launch vehicles capable of carrying large versions of the Progress (i.e., Modified Progress and Progress MT) could also carry smaller versions. For example, the Ariane V can carry all Progress versions even though only the Progress MT is shown in Table 62.

Finally, it should be noted that existing expendable launch vehicle upper stages could be modified to perform the autonomous rendezvous and docking function. Beyond modification of existing upper stages for autonomous rendezvous and docking capability, similar modifications could be made to other stages that have been used in the past as orbit transfer or injection stages. Table 64 shows the potential capabilities of the applicable United States launch vehicles with modified upper stages. For preliminary capability estimation purposes, the potential usable cargo and carrier weights of the vehicles in Table 64 were reduced by 1,000 pounds for the addition of autonomous rendezvous and docking avionics and related hardware.

Transportation Implications with Russian Participation

Figure 120 shows the Space Shuttle and Proton performance as a function of the Space Station inclination. The Space Shuttle capabilities on the figure are for a variety of different external tank and solid rocket motor configurations. Also, these capabilities are 1,200 pounds greater than those tabulated in Table 62 to account for the lower launch package integrator weight for an assembly flight. Proton performance is shown for the Block DM (Proton fourth stage) and the Salyut space tug. Because of the inherent capabilities of each vehicle when launched by the Proton, the Block DM would only be used when delivering payloads to low inclinations (less than about 45 degrees) while the Salyut space tug would be used exclusively for payloads to high inclinations (greater than about 45 degrees). The exception to the Block DM at low inclinations is when Mir-2 technology modules would be delivered. Since the Salyut space tug is planned to be integrated with these modules for launch to Mir-2, it is reasonable that this configuration also be used for launch to the Space Station, although some penalty is incurred in terms of the lowest achievable inclination.

When considering the elements that might be delivered by the Space Shuttle or Proton, a natural division into high and low weight ranges is apparent. The high weight range includes the Japanese Experiment Module, Attached Pressurized Module, pressurized logistics carrier, Mir-1 modules and the Mir-2 core module. The low weight range includes the Mir-2 technology modules, Soyuz TM (with and without crew), the Progress M and the mini-pressurized logistics carrier. The limits on the high weight range were established by the current maximum program allowable weight, 31,800 pounds (i.e., standard Space Shuttle capability at 28.8 degrees, 220 nautical miles), and the maximum achievable weight by a Space Shuttle equipped with advanced solid rocket motors and aluminum lithium external tank at 51.6 degrees and 220 nautical miles altitude (38,500 pounds). The low weight range limits were established by the Soyuz without crew (approximately 15,000 pounds) and the Mir-2 technology modules (approximately 17,000 pounds).

Several key Proton limitations are apparent from the Figure 120. Although the maximum Proton capability considering range safety limitations is at 51.6 degrees, there is no Proton assembly capability for high weight range elements below about 48 degrees. The Titan IV and Salyut space tug and the growth version of the Ariane V with the ESA Automated Transfer

Table 62
Launch vehicle capabilities to 220 nautical miles circular orvbit
(logistics performance shown for Space Shuttle)

	Usable Cargo and Carrier Weight[1]		Approximate Usable Payload Envelope
Vehicle	**28.8°**	**51.6°**	**(diameter x length, ft.)**
Space Shuttle with Standard ET	30,600	17,800	15 x 60[2]
Space Shuttle with Al/Li ET	38,100	25,300	15 x 60[2]
Space Shuttle with ASRM-10	40,600	27,800	15 x 60[2]
Space Shuttle with ASRM-12	42,600	29,800	15 x 60[2]
Space Shuttle with ASRM-10 and Al/Li ET	48,100	35,300	15 x 60[2]
Space Shuttle with ASRM-12 and Al/Li ET	50,100	37,300	15 x 60[2]
Atlas IIAS/Modified Progress	~7,000	~7,000	7 x 14
Titan III/Progress MT	~13,000	~13,000	10 x 27
Titan IV/Progress Derived Transfer Stage	~38,000	~37,000	16 x 50
Titan IV/Salyut Space Tug	~41,000	~38,000	16 x 50
Ariane 44L/Modified Progress	~7,000	~7,000	7 x 14
Ariane 5/Progress MT	~13,000	~13,000	10 x 27
Ariane 5/ATV	36,400	33,700	15 x 31
Growth Ariane 5/ATV	40,800	38,100	15 x 31
H-II/Modified Progress	~7,000	~7,000	7 x 14
Soyuz/Progress M	≈51.6°[3]	~4,000	7 x 8.5
Proton/Progress M	≈33°[3]	~4,000	7 x 8.5
Proton/Progress MT	≈45°[3]	~13,000	7 x 20
Zenit/Progress MT	≈51.6°[3]	~13,000	7 x 20
Proton/Progress Derived Transfer Stage	≈51.6°[3]	~37,000	16 x 50
Proton/Salyut Space Tug	~6,000	~38,500	16 x 50

1. Progress M, Modified Progress M, and Progress MT vehicles do not require a separate carrier; weights shown for these versions of Progress are cargo contained within the Progress vehicle itself, *not* the weight of the Progress and cargo.
2. Standard shuttle payload bay length. Volume available for a particular payload is flight dependent.
3. No capability at 28.8 degrees. Minimum inclination capability shown.

Key: Al/Li-aluminum lithium; ET-external tank; ATV-autonomous transfer vehicle; ASRM 10-advanced solid rocket motor with 10 Klbs increased payload capability; ASRM 12-advanced solid rocket motor with 12 Klbs increased payload capability

Table 63
Space Shuttle capabilities to 220 nautical miles circular orbit

Space Shuttle Configuration	Capability (lbs.) @ 28.8° Launch Package Int. Weight (lbs.) 0	6,000	7,200	Capability (lbs.) @ 51.6° Launch Package Int. Weight.(lbs.) 0	6,000	7,200
Standard ET	37,800	31,800	30,600	25,000	19,000	17,800
Al/Li ET	45,300	39,300	38,100	32,500	26,500	25,300
ASRM-10	47,800	41,800	40,600	35,000	29,000	27,800
ASRM-12	49,800	43,800	42,600	37,000	31,000	29,800
ASRM-10 and Al/Li ET	55,300	49,300	48,100	42,500	36,500	35,300
ASRM-12 and Al/Li ET	57,300	51,300	50,100	44,500	38,500	37,300

Key: Al/Li-aluminum lithium
ET-external tank
ATV-autonomous transfer vehicle
ASRM 10-advanced solid rocket motor with 10 Klbs increased payload capability
ASRM 12-advanced solid rocket motor with 12 Klbs increased payload capability

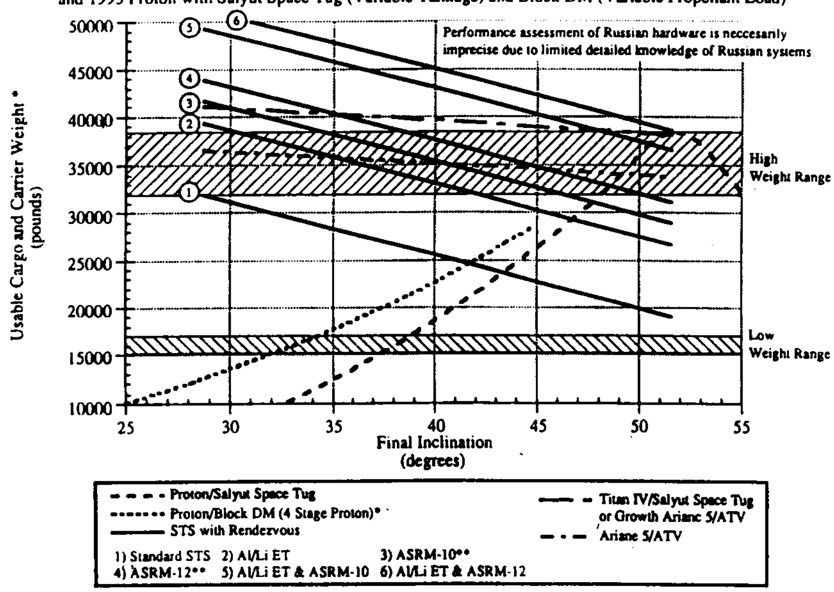
Table 64
Launch vehicle capabilities to 220 nautical miles circular orbit
(Upper stage modified for AR&D)

Vehicle	Potential Usable Cargo and Carrier Weight (lbs.) 28.8°	51.6°
Delta II	10,000	9,000
Atlas IIAS	16,000	15,000
Titan III	20,000	19,000
Titan IV	36,000	34,000

Vehicle are also capable of delivering all Space Station assembly elements in the high weight range to inclinations at or below 51.6 degrees. The standard ArianeV with the automated transfer vehicle, although somewhat less capable, is still able to lift payloads in excess of the current maximum program allowable (31,800 pounds) to 51.6 degrees. The Titan IV and Ariane V capabilities are also shown in Figure 120. Three inclination discriminators are drawn from the low weight range. The first is the Salyut space tug's ability to deliver the Mir-2 Technology Modules to approximately 39 degrees. Next is the Block DM delivery of a Soyuz with crew to 36 degrees. Third, the Progress or Soyuz without crew could be delivered as low as 33 degrees.

A summary of the Russian participation options is shown in Table 65.

Capability to 220 nmi Circular Orbit as a Function of Inclination for STS, Titan IV/Salyut Space Tug, Ariane 5/ATV, and 1995 Proton with Salyut Space Tug (Variable Tankage) and Block DM (Variable Propellant Load)



* When Proton/Block DM delivers Progress or Modified Progress, usable cargo weight is volume limited to 4,000 lb or 7,000 lb, respectively.

** ASRM-10 & ASRM-12 refer to ASRM configurations yielding 10,000 lb and 12,000 lb greater lift capability, respectively, than the standard configuration shuttle.

Figure 120
STS, Titan IV, Ariane V and Proton capabilities

Table 65
Russian transportation participation options

Russian Transportation Participation Desired	Required STS Configuration	Maximum Space Station Inclination	STS Maximum Delivery Capability	Russian Delivery Options
None	Standard ET	28.8°(1)	31,800 lb	None
Low Weight Range Elements	Al/Li ET	39° - 42°	33,500 lb - 31,800 lb	Soyuz TM (with & without crew) Progress M MIR-2 Tech. Modules mini-PLC
High Weight Range Elements(2)	ASRM-10(3) ASRM-12(3) Al/Li ET & ASRM-10 Al/Li ET & ASRM-12	~46° ~50° 51.6° 51.6°	31,800 lb 31,800 lb 36,500 lb 38,500 lb	JEM, APM MIR-1 Modules MIR-2 Core Mod. PLC

(1) Even without Russian transportation participation, space station inclination can be higher based on other requirements (e.g. science requirements) if space station element weights allow or the program invests in greater shuttle capability.

(2) If ASRMs are unavailable, maximum space station inclination is limited to 42° and Russian transportation participation is confined to elements in the low weight range.

(3) ASRM-10 & ASRM-12 refer to ASRM configurations yielding 10,000 lb and 12,000 lb greater shuttle lift capability, respectively, than the standard configuration shuttle.

Appendix F

SPACE STATION OPTION RATING BY RESEARCH DISCIPLINE

Discipline	SSF at PHC	Option A HTC	Option A PHC	Option B HTC	Option B PHC	Option C PHC Solar Inertial	Option C PHC Local Vertical
Scientific & Commercial Microgravity							
Biotechnology							
Protein Crystal Growth (c)	3	2	3	2	3	3	3
Cell Tissue (c)	3	2	3	2	3	3	3
Materials Science							
Electronic & Photonic Materials (d)	3	3 / 1 (g)	3	3 / 1 (g)	3	1	3 (h)
Metals & Alloys (d)	3	3 / 1 (g)	3	3 / 1 (g)	3	2	3 (h)
Glasses & Ceramics (d)	3	3 / 1 (g)	3	3 / 1 (g)	3	2	3 (h)
Fluids	3	2	3	3	3	2	3 (h)
Combustion	3	2	3	3	3	2	3 (h)
Life Sciences							
Grav. Bio. (short-term) (a)	3	3	3	3	3	3	3
Grav. Bio. (long-term) (a)	3 (b)	0	3 (b)	0	3 (b)	3 (b)	3 (b)
Human Physiology (short-term) (a)	3	3	3	3	3	3	3
Human Physiology (long-term) (a)	3	0	3	0	3	3	3
Radiation Biology (short-term) (a)	3	3	3	3	3	3	3
Radiation Biology (long-term) (a)	3	0	3	0	3	3	3
Controlled Ecological Life Support (a)	3	0	3	0	3	3	3
Environmental Health (short-term)	3	3	3	3	3	3	3
Environmental Health (long-term)	3	0	3	0	3	3	3
Operational Medicine (short-term)	3	3	3	3	3	3	3
Operational Medicine (long-term)	3	1	3	1	3	3	3
Human Factors (short-term) (a)	3	3	3	3	3	3	3
Human Factors (long-term) (a)	3	0	3	0	3	3	3
Exobiology (short-term)	3	3	3	3	3	3	3
Exobiology (long-term)	3	0	3	0	3	3	3
Engineering Research							
Robotics	3	3	3	3	3	3	3
Envir. Effects (atomic)	3	1	1	2	3	1	2
Envir. Effects (orbital debris)	3	1	1	2	3	1	2
Structures	3	2	3	2	3	1 (e)	1 (e)
Communications & Information Systems	3	3	3	3	3	3	3
Propulsion	3	3	3	3	3	3	3
Fluid Management	3	3	3	3	3	3	3
Human Support	3	3	3	3	3	3	3
Space Science							
Sensor Development	1	1	1	1	5	2	5
Atmospheric Science	3	1	1	3	3	1	1 / 3 (f)
Earth Observing Science	2	0	0	2	2	0	2

<u>Scale: 0 to 5</u>

0 no capability
1 significantly degraded capability
2 degraded capability
3 meets minimum guidelines capability
4 enhanced guidelines capability
5 significantly enhanced guidelines capablilty

<u>Notes:</u>

(a) Requires normoxic and 0.3% CO_2
(b) Requires Centrifuge/Habitat Holding Facilities
(c) Requires approximately 30-day increments with stable microgravity environment
(d) HTC ground-tended ops assumed
(e) Large truss structure unavailable
(f) LVL-x/LVL-y attitudes
(g) Utilization flight/ground tended

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